Joint 9th IDPASC SCHOOL and
XXXI INTERNATIONAL SEMINAR of NUCLEAR and
SUBNUCLEAR PHYSICS "Francesco Romano"
28/5 - 3/6 2019

HEP Theory
(part 2)

Michelangelo L. Mangano
Theory Department, CERN, Geneva

Key question for the future developments of HEP: Why don't we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:
- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Remark

the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field

The physics potential (the "case") of a future facility for HEP should be weighed against criteria such as:

(1) the **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) the **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*
- exploit both direct (large Q^2) and indirect (precision) probes

(3) the potential to provide conclusive **yes/no answers** to relevant, broad questions.

What we want from a future collider

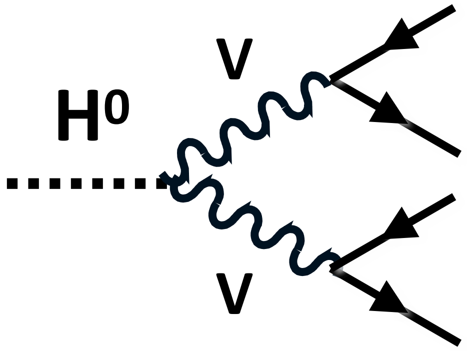
- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**

- Exploration potential:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*

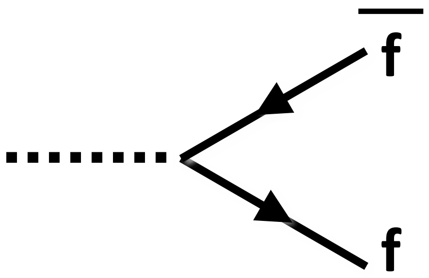
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Higgs observables: decay BRs

Tree-level couplings



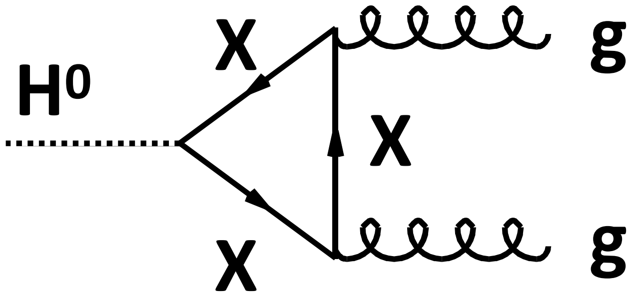
coupling to EW gauge bosons ⇒ g,g’



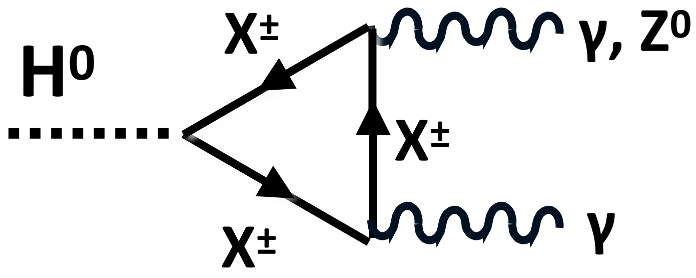
coupling to fermions
⇒ m_f / v

$m_f < m_H / 2$

Loop-level couplings



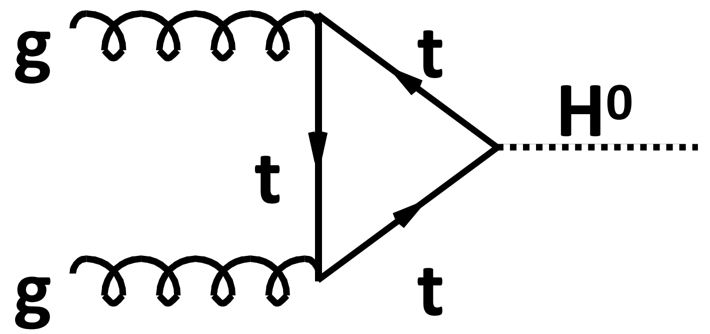
X_{SM} =t,b,c X_{BSM} = T, stop, …?

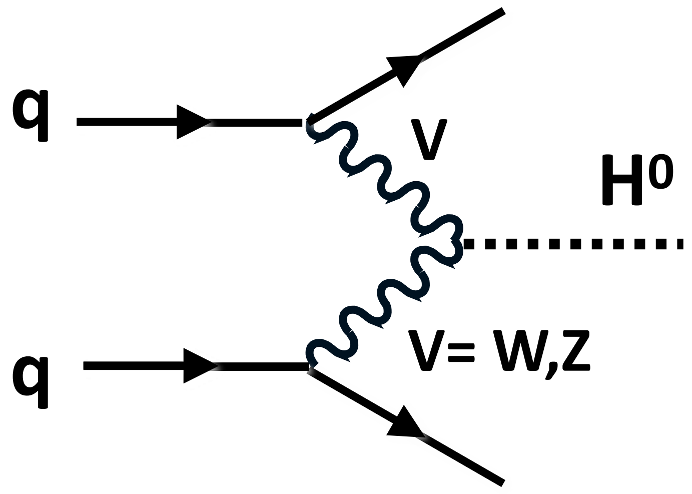


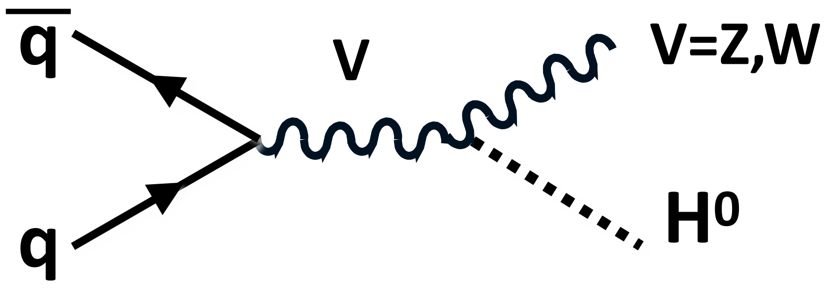
X_{SM} =t, W± X_{BSM} = T, stop, chargino, …?

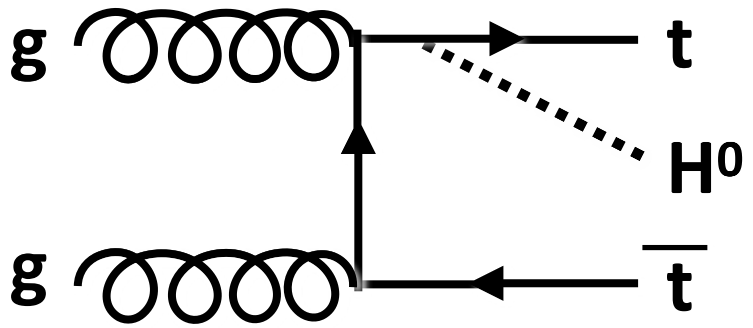
Higgs observables: production rates

Hadronic collisions

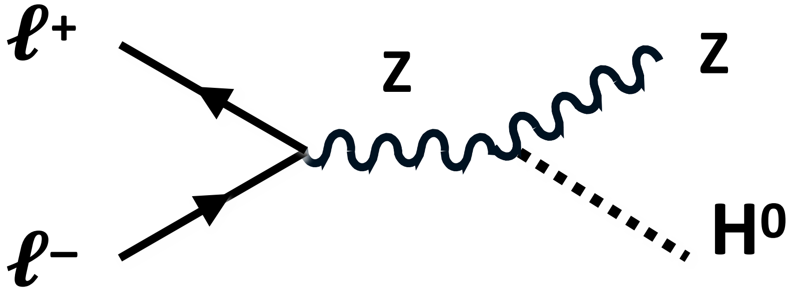


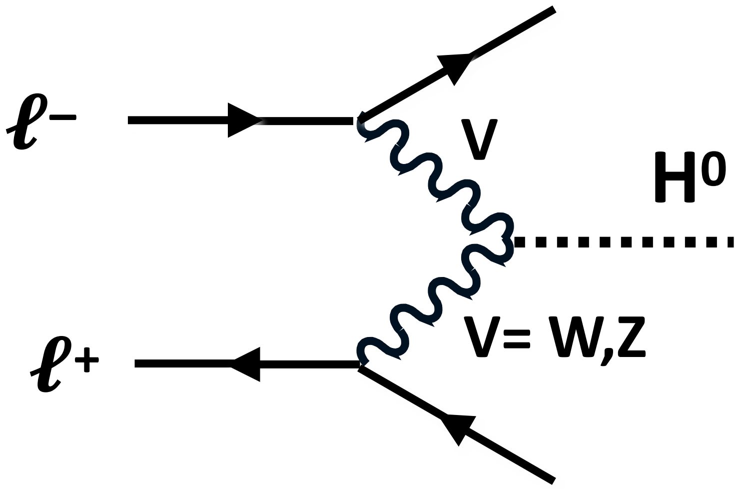


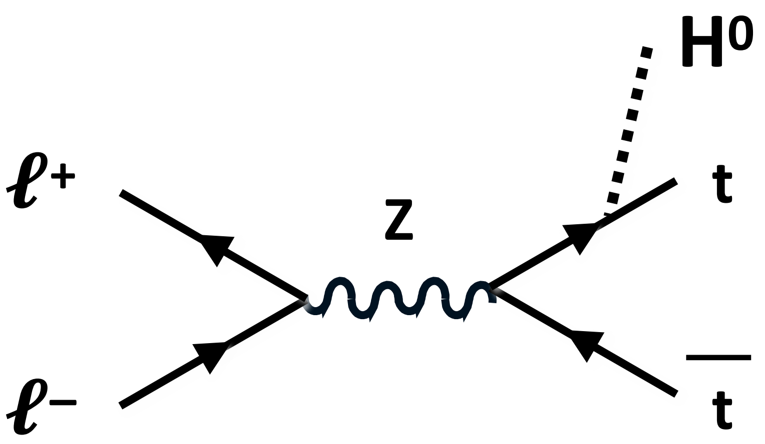




Laptonic collisions

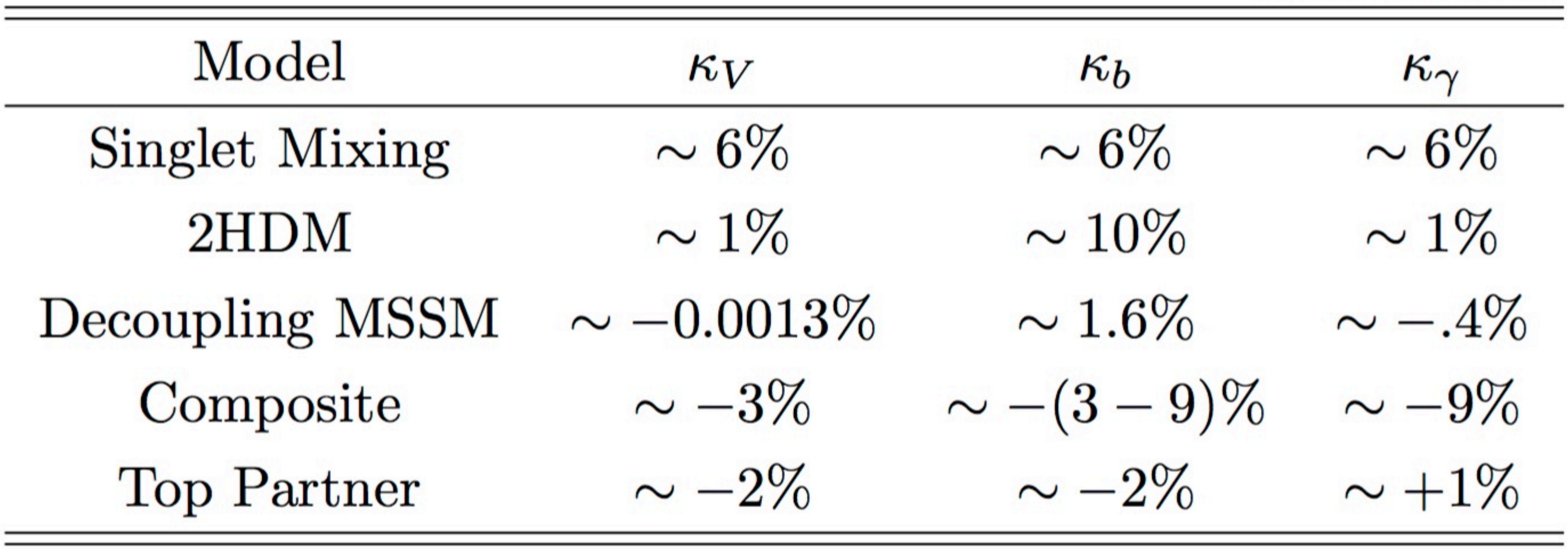






Sensitivity of various Higgs couplings to examples of beyond-the-SM phenomena

arXiv:1310.8361



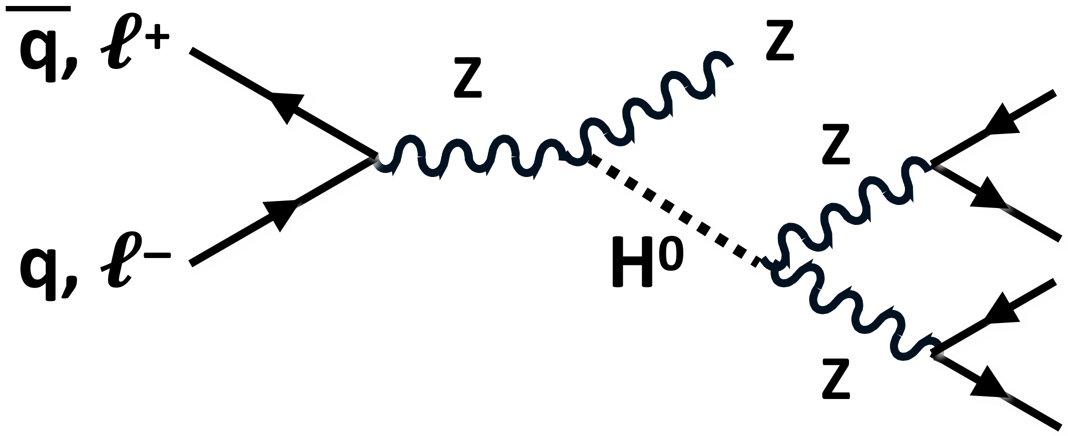
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

=> the goal should be (sub)percent precision!

Extracting couplings from measurements

Example

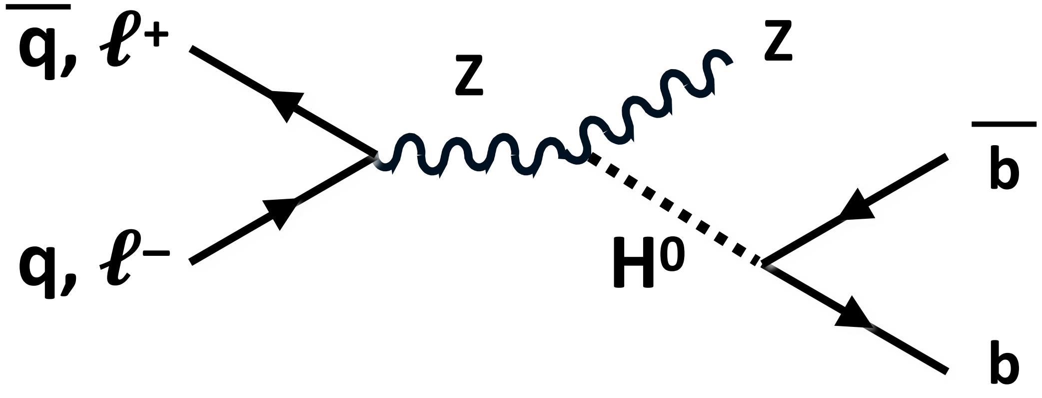
(A)



$$\sigma\left(pp/ee \to ZH[\to ZZ^*]\right) \propto g_{HZZ}^2 \times \underbrace{\boxed{\frac{g_{HZZ}^2}{\Gamma_H}}}_{B(H\to ZZ^*)}$$

1 measurement, 2 parameters!

(B)



$$\sigma\left(pp/ee \to ZH[\to b\bar{b}]\right) \propto g_{HZZ}^2 \times \underbrace{\boxed{\frac{g_{Hbb}^2}{\Gamma_H}}}_{B(H\to b\bar{b})}$$

1 new measurement, but
1 more parameter…

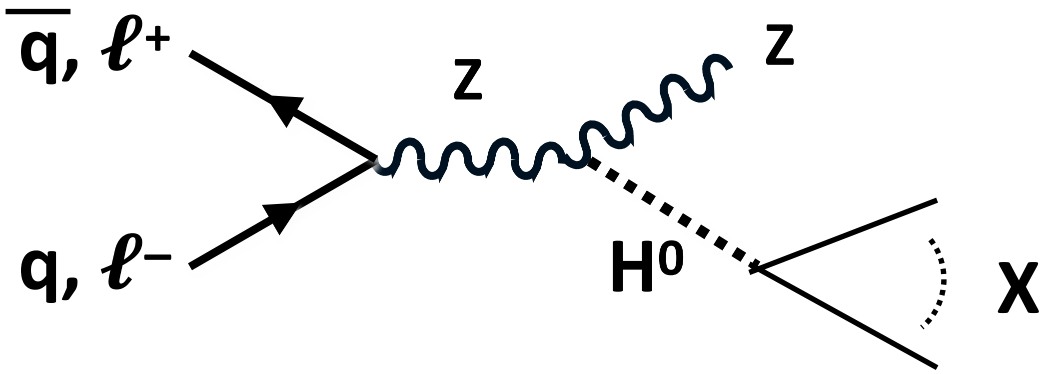
… little progress, except we now know

$$\frac{g_{HZZ}^2}{g_{Hbb}^2} = \frac{\sigma_A}{\sigma_B}$$

Overall constraint: $\sum_X B(H \to X) = 1$

Therefore:

$$\sum_X \sigma\Big($$

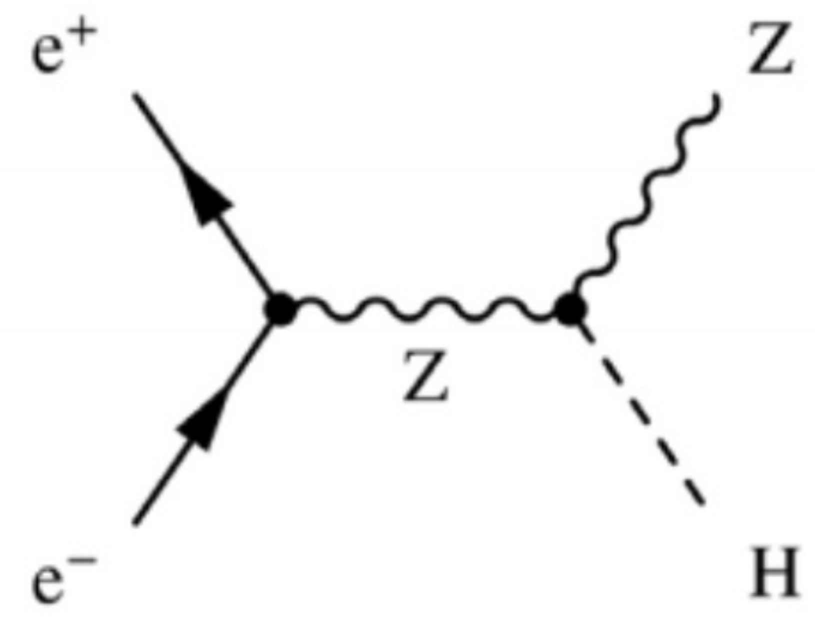


$$\Big) = \sigma(ZH) \propto g^2_{HZZ}$$

How can we hope to detect ALL possible decays of the Higgs boson??

If the goal is to test its properties, we cannot make assumptions, and must be open to possible unexpected decays, possibly invisible, like H→dark matter…

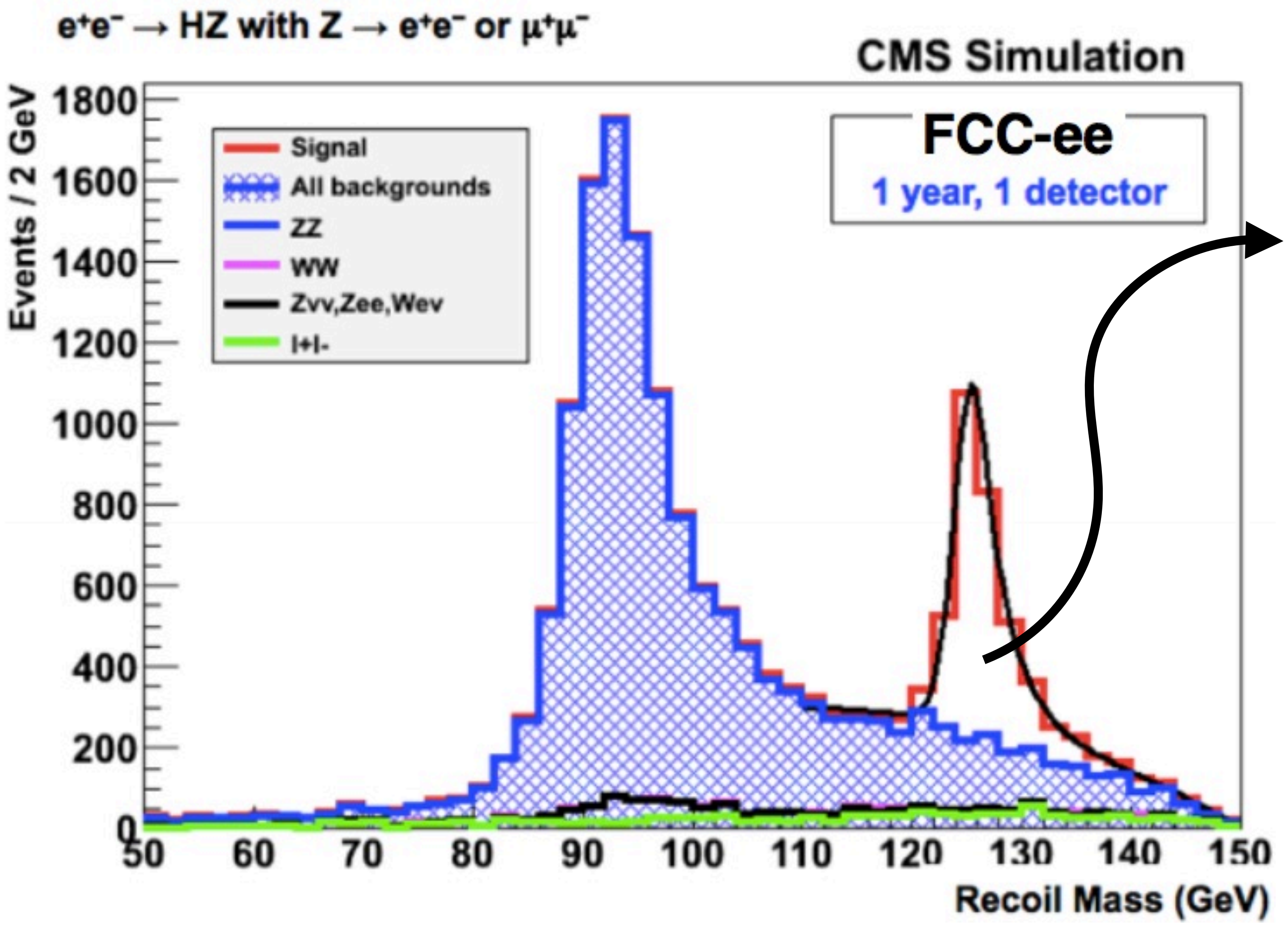
An $\ell^+\ell^-$ collider provides the solution ….



$p(H) = p(e^-e^+) - p(Z)$

=> $[\, p(e^-e^+) - p(Z) \,]^2$ peaks at $m^2(H)$

reconstruct Higgs events independently of the Higgs decay mode!

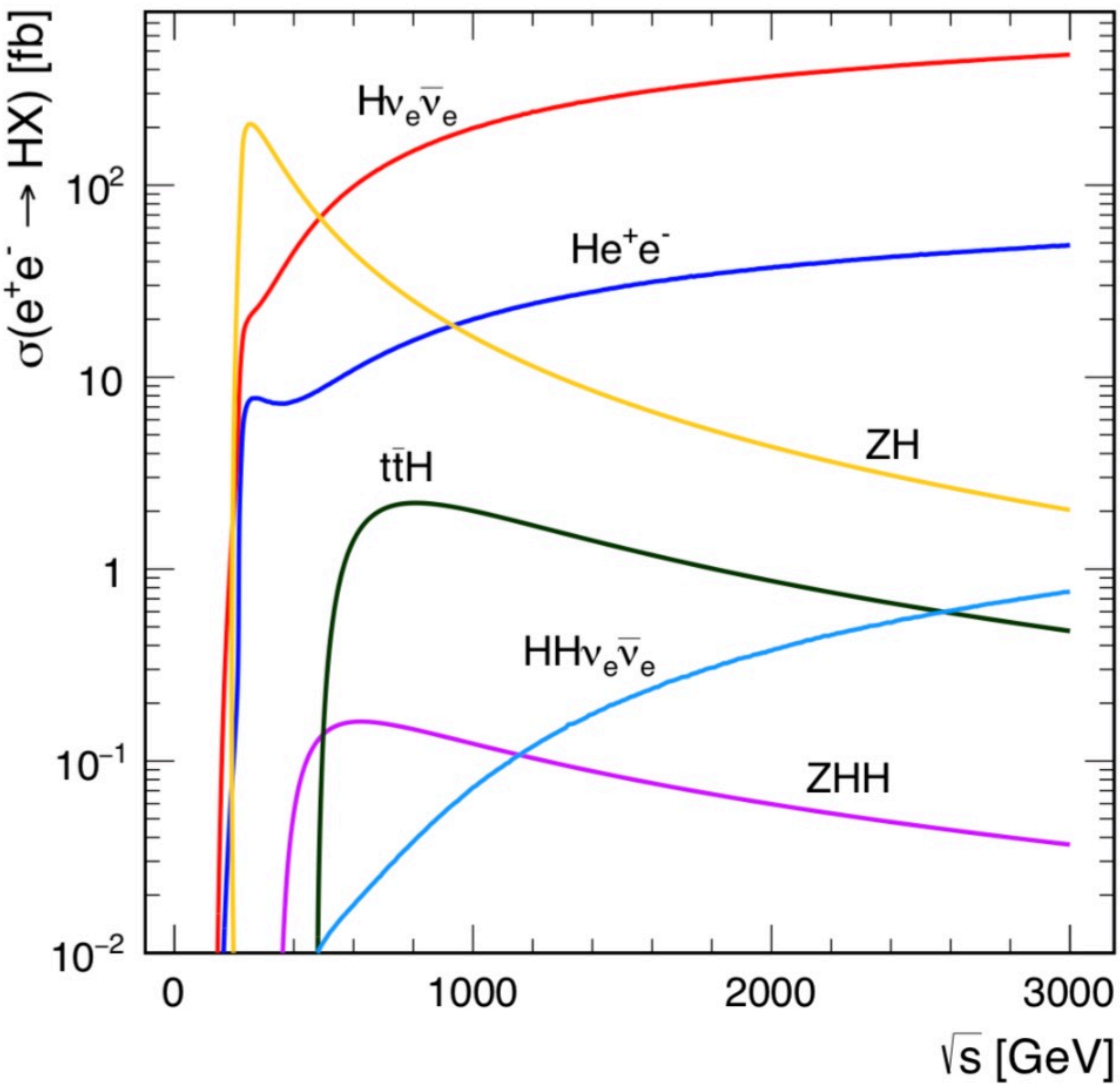


$N(ZH) \propto \sigma(ZH) \propto g_{HZZ}^2$

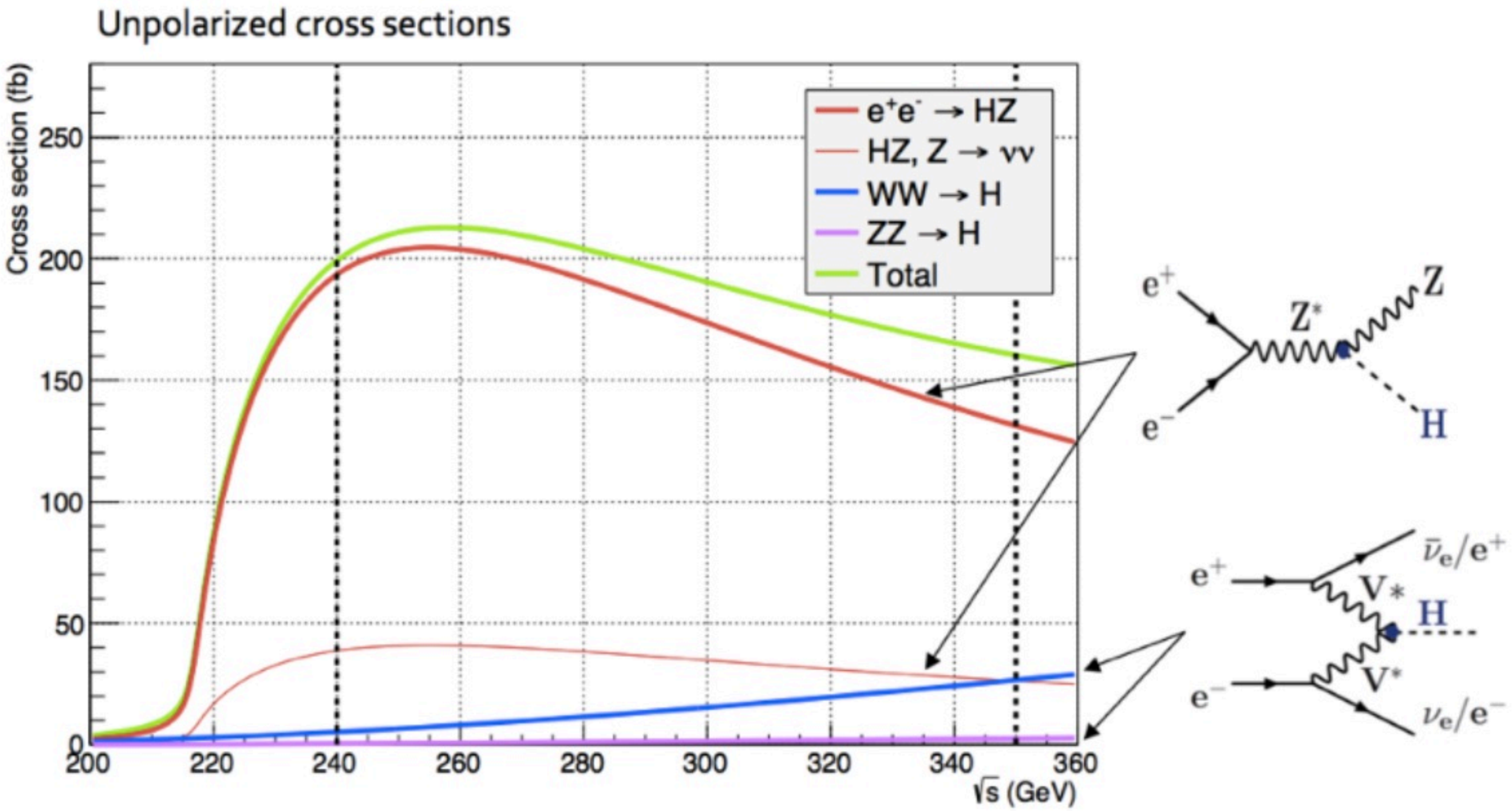
$N(ZH[\to ZZ]) \propto$
$\sigma(ZH) \times BR(H \to ZZ) \propto$
$g_{HZZ}^2 \times g_{HZZ}^2 / \Gamma(H)$

=> absolute measurement of width and couplings

$m_{recoil} = \sqrt{[\, p(e^-e^+) - p(Z) \,]^2}$

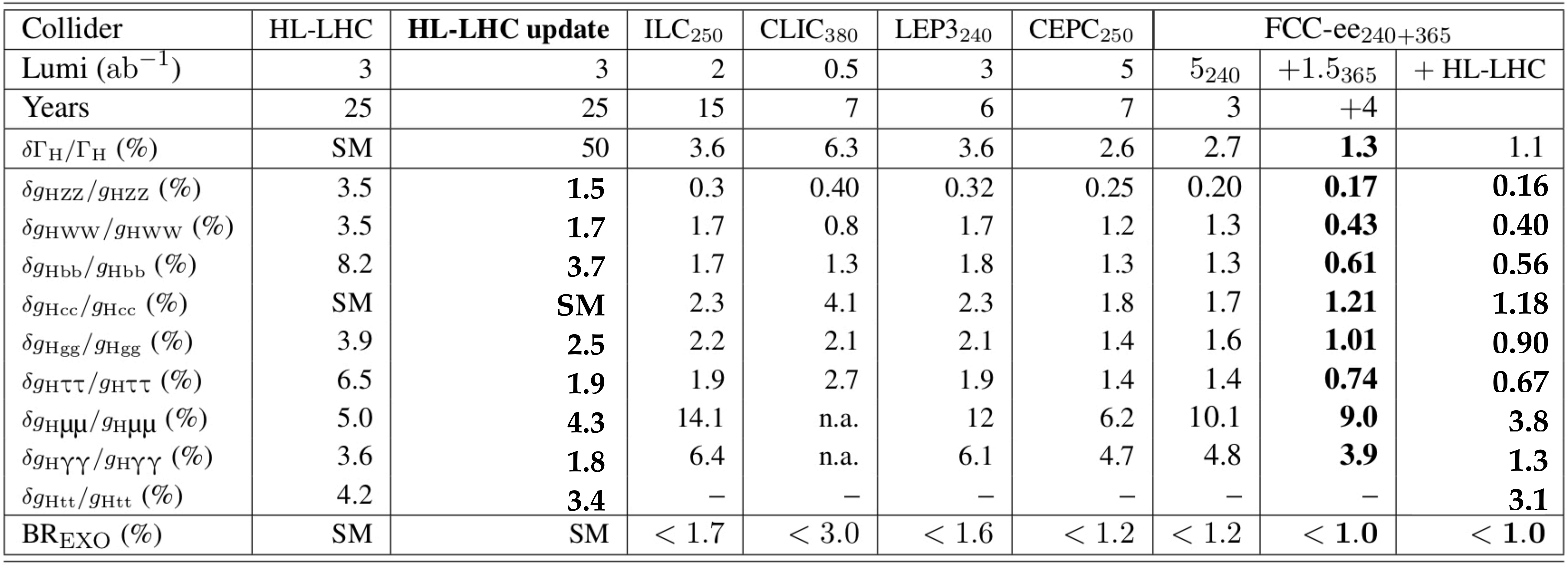

$\sigma(e^+e^- \to HX)$ [fb]
$\sqrt{s}$ [GeV]
$H\nu_e\bar{\nu}_e$
He^+e^-
ZH
$t\bar{t}H$
$HH\nu_e\bar{\nu}_e$
ZHH
10^2
10
1
10^{-1}
10^{-2}
0
1000
2000
3000

FCC-ee



	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
# Higgs bosons from e+e-→HZ	1,000,000	200,000
# Higgs bosons form fusion process	25,000	40,000

Higgs couplings: beyond the HL-LHC



Collider	HL-LHC	**HL-LHC update**	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240+365}$		
Lumi (ab^{-1})	3	3	2	0.5	3	5	5$_{240}$	+1.5$_{365}$	+ HL-LHC
Years	25	25	15	7	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	50	3.6	6.3	3.6	2.6	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	**1.5**	0.3	0.40	0.32	0.25	0.20	**0.17**	**0.16**
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	**1.7**	1.7	0.8	1.7	1.2	1.3	**0.43**	**0.40**
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	**3.7**	1.7	1.3	1.8	1.3	1.3	**0.61**	**0.56**
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	**SM**	2.3	4.1	2.3	1.8	1.7	**1.21**	**1.18**
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	**2.5**	2.2	2.1	2.1	1.4	1.6	**1.01**	**0.90**
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	**1.9**	1.9	2.7	1.9	1.4	1.4	**0.74**	**0.67**
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	**4.3**	14.1	n.a.	12	6.2	10.1	**9.0**	**3.8**
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	**1.8**	6.4	n.a.	6.1	4.7	4.8	**3.9**	**1.3**
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	**3.4**	–	–	–	–	–	–	**3.1**
BR$_{EXO}$ (%)	SM	SM	< 1.7	< 3.0	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

Table 1: Relative statistical uncertainty on the Higgs boson couplings and total decay width, as expected from the FCC-ee data, and compared to those from HL-LHC and other e^+e^- colliders exploring the 240-to-380 GeV centre-of-mass energy range. All numbers indicate 68% CL intervals, except for the last line which gives the 95% CL sensitivity on the "exotic" branching fraction, accounting for final states that cannot be tagged as SM decays. The FCC-ee accuracies are subdivided in three categories: the first sub-column give the results of the model-independent fit expected with 5 ab^{-1} at 240 GeV, the second sub-column in bold – directly comparable to the other collider fits – includes the additional 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV, and the last sub-column shows the result of the combined fit with HL-LHC. The fit to the HL-LHC projections alone (first column) requires two additional assumptions to be made: here, the branching ratios into $c\bar{c}$ and into exotic particles are set to their SM values.

* M. Cepeda, S. Gori, P. J. Ilten, M. Kado, and F. Riva, (conveners), et al, *Higgs Physics at the HL-LHC and HE-LHC*, CERN-LPCC-2018-04, https://cds.cern.ch/record/2650162.

Remarks and key messages

- Updated HL-LHC projections bring the coupling sensitivity to the few-% level. They are obtained by extrapolating **current** analysis strategies, and are informed by current experience plus robust assumptions about the performance of the phase-2 upgraded detectors in the high pile-up environment
    - Projections will improve as **new** analyses, allowed by higher statistics, will be considered

1. To significantly improve the expected HL-LHC results, future facilities must push Higgs couplings' precision to the sub-% level
2. Event rates higher than what ee colliders can provide are needed to reach sub-% measurements of couplings such as Hγγ, Hμμ, HZγ, Htt

The unique contributions of a *100 TeV pp collider to Higgs physics*

- Huge Higgs production rates:
  - access (very) rare decay modes
  - push to %-level Higgs self-coupling measurement
  - new opportunities to reduce syst uncertainties (TH & EXP) and push precision

- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst uncertainties (TH and EXP)
  - different hierarchy of production processes
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*eg decay BRs*) at $Q \sim m_H$

- High energy reach
  - direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition
    - …

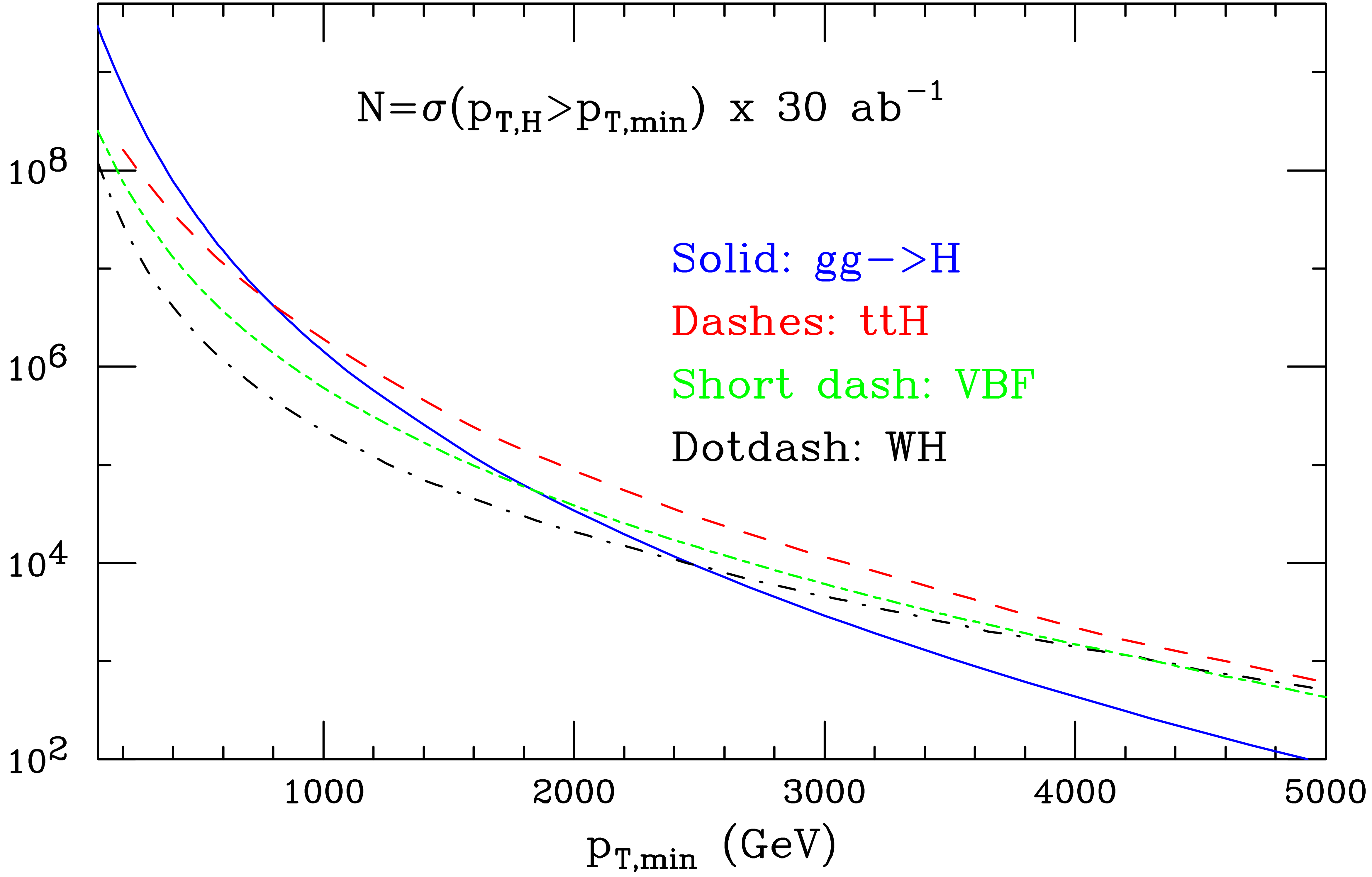
SM Higgs: event rates in pp@100 TeV

	$gg \to H$	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 30\ \mathrm{ab}^{-1}$

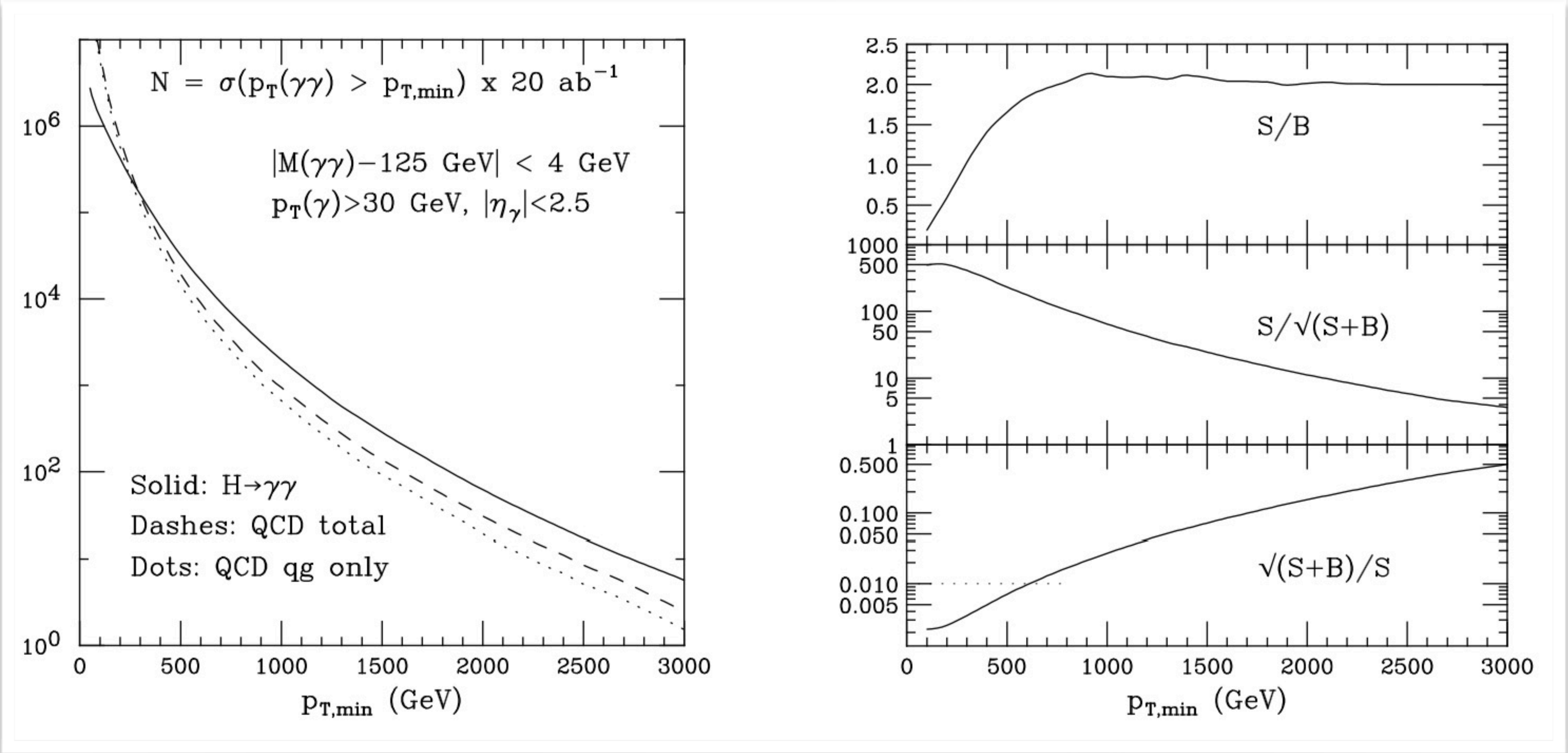
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

H at large p_T



- Hierarchy of production channels changes at large $p_T(H)$:
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

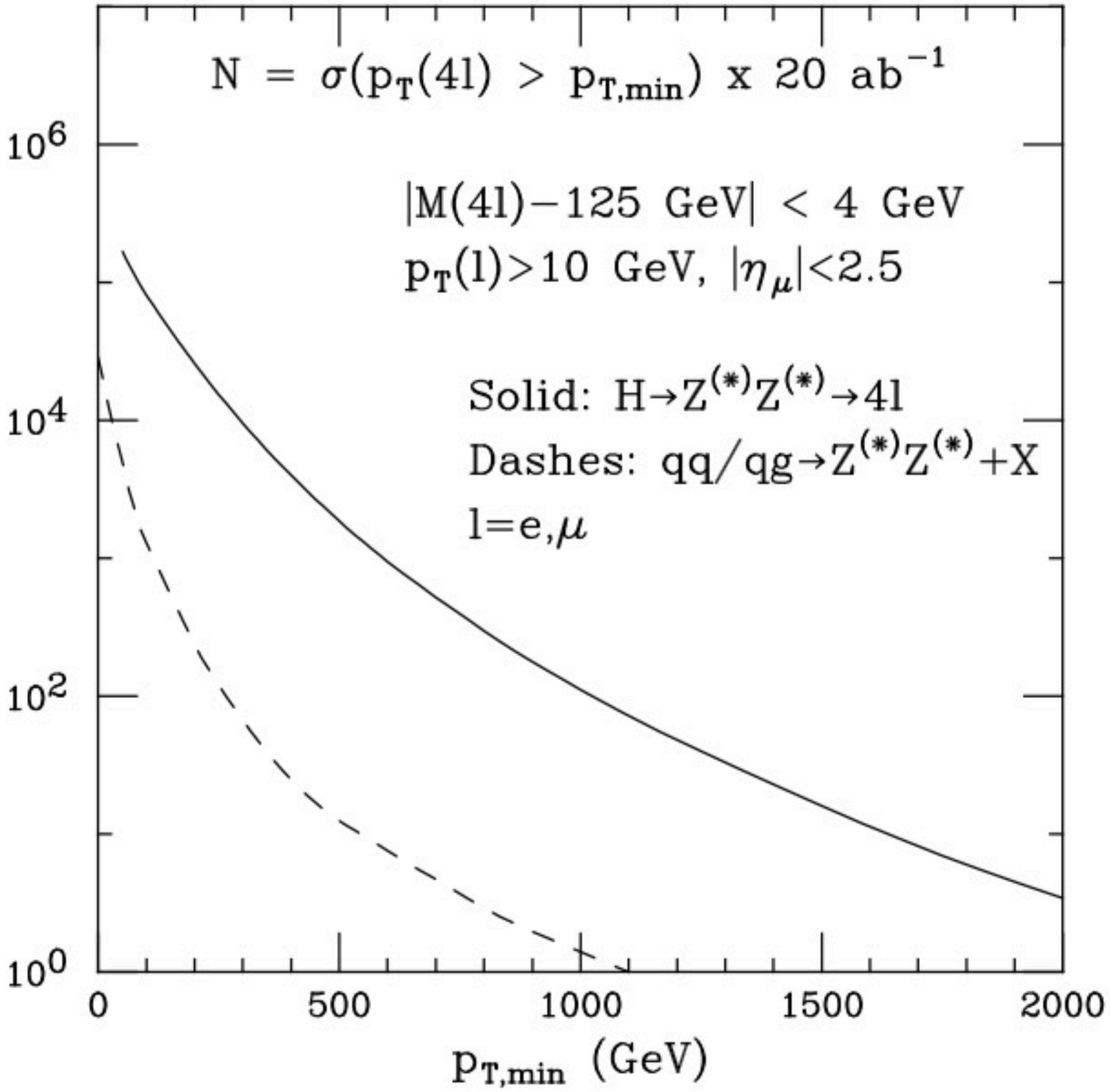
gg→H→γγ at large p_T

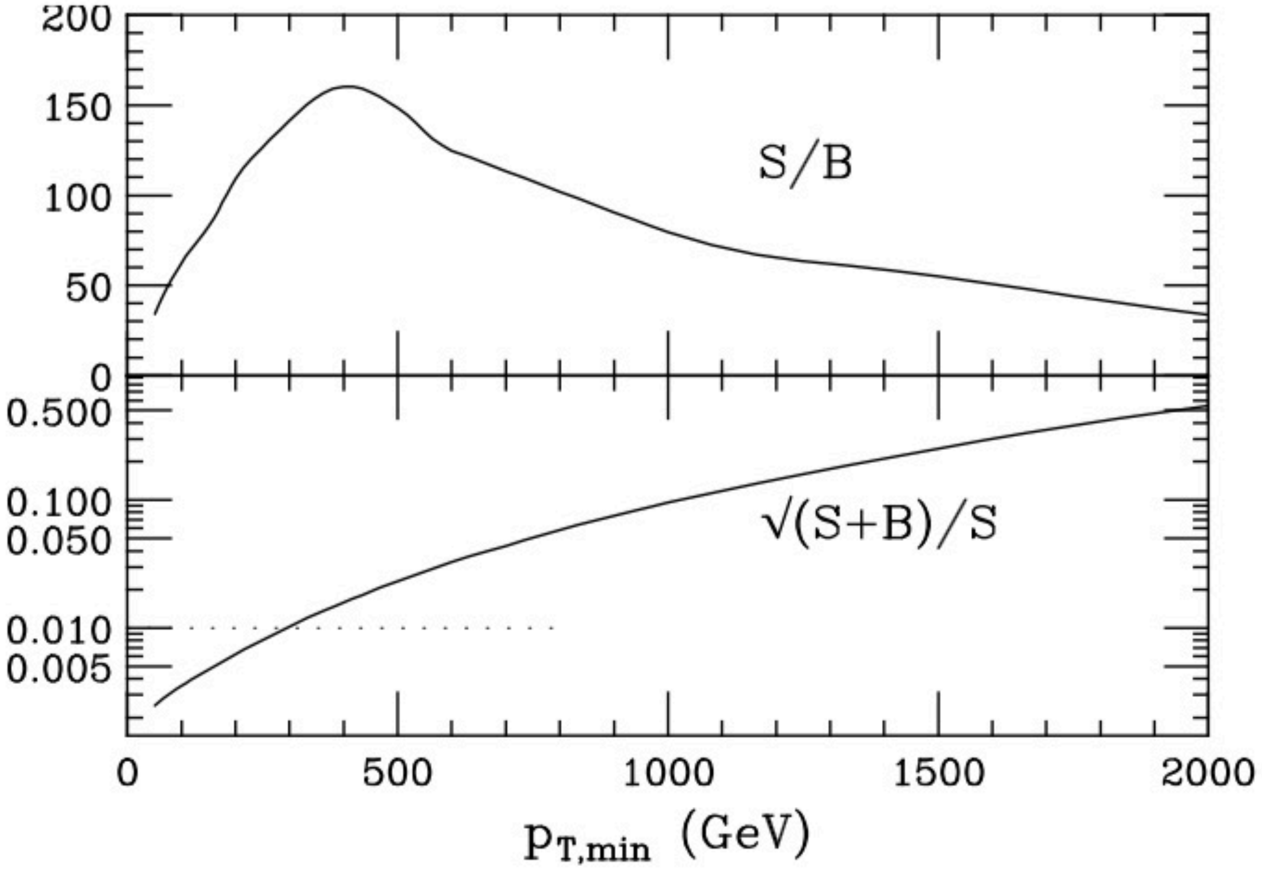


- At LHC, S/B in the H→γγ channel is O(few %)
- At FCC, for $p_T(H) > 300$ GeV, S/B~1
- Potentially accurate probe of the H pt spectrum up to large pt

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

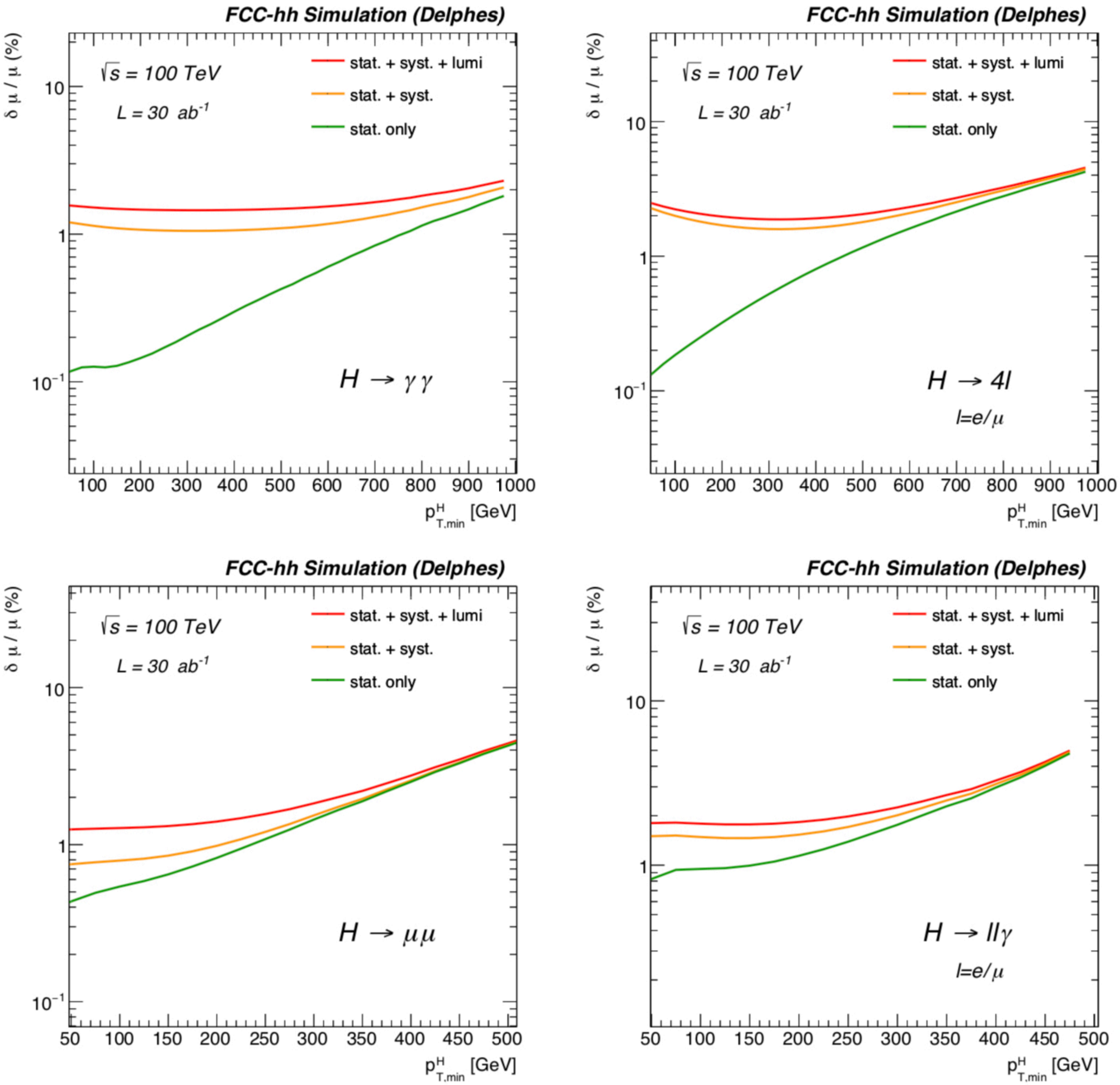
$gg \to H \to ZZ^* \to 4l$ at large p_T

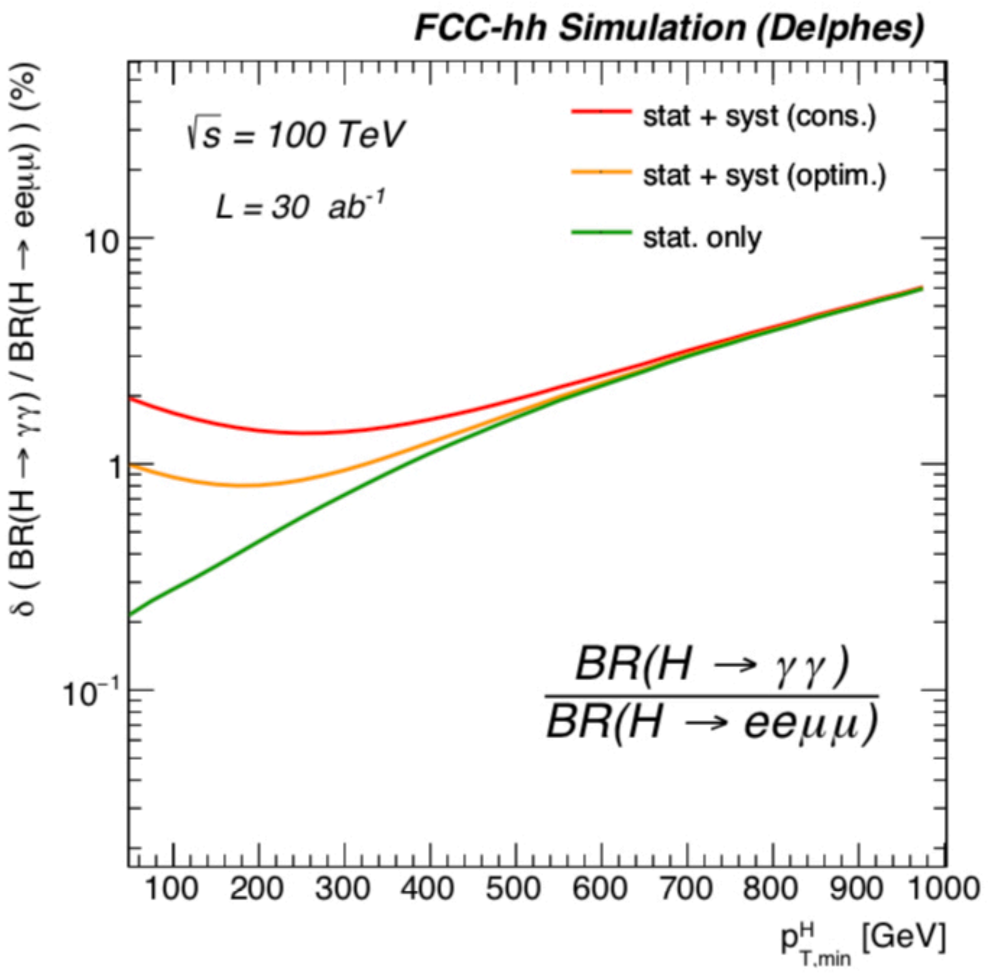


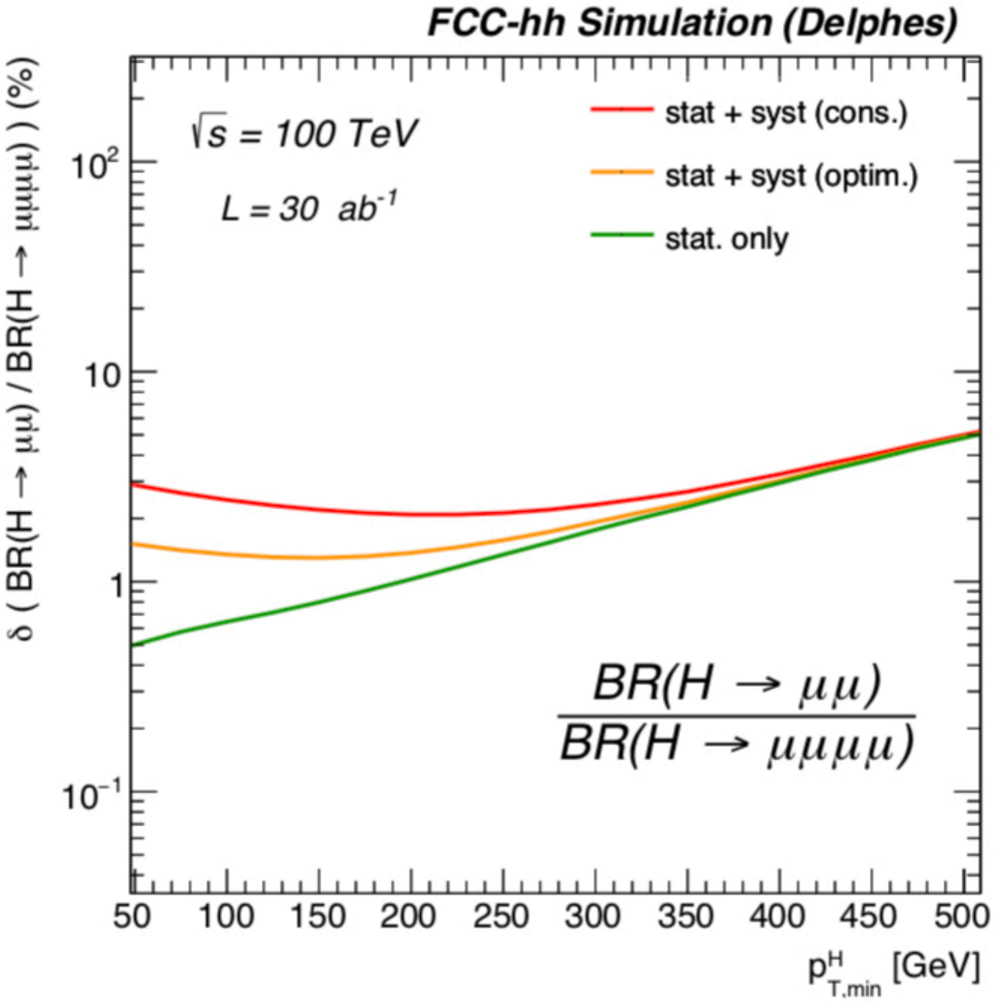


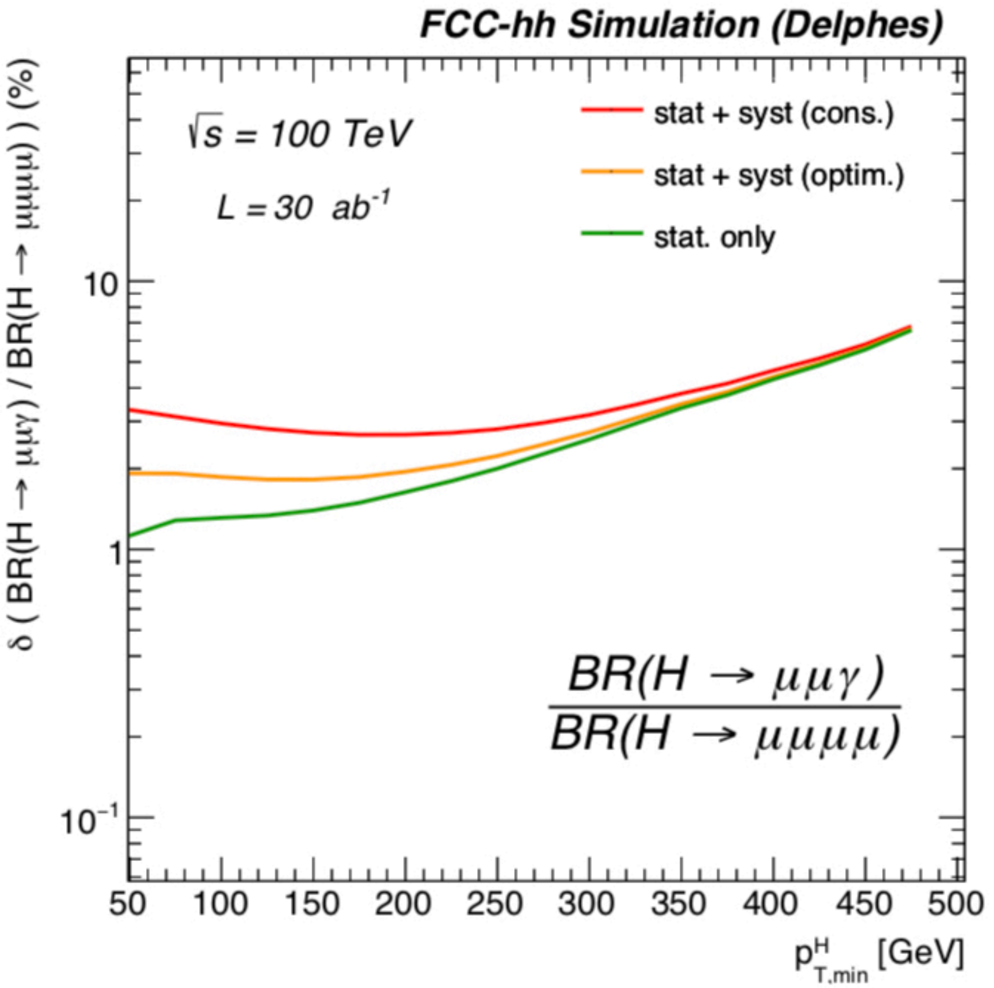
- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.3%**
300	**1%**
1000	10%


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat. + syst. + lumi
stat. + syst.
stat. only
$H \to \gamma\gamma$
$H \to 4l$
$l=e/\mu$
$H \to \mu\mu$
$H \to ll\gamma$
$l=e/\mu$
$\delta\mu/\mu$ (%)
$p_{T,min}^{H}$ [GeV]
10^{-1}
1
10
50
100
150
200
250
300
350
400
450
500
600
700
800
900
1000


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \gamma\gamma)}{BR(H \to ee\mu\mu)}$
δ (BR(H → γγ) / BR(H → eeμμ)) (%)
10
1
10^{-1}
100
200
300
400
500
600
700
800
900
1000
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμ) / BR(H → μμμμ)) (%)
10^{2}
10
1
10^{-1}
50
100
150
200
250
300
350
400
450
500
$p_{T,min}^{H}$ [GeV]


FCC-hh Simulation (Delphes)
$\sqrt{s}$ = 100 TeV
L = 30 ab^{-1}
stat + syst (cons.)
stat + syst (optim.)
stat. only
$\frac{BR(H \to \mu\mu\gamma)}{BR(H \to \mu\mu\mu\mu)}$
δ (BR(H → μμγ) / BR(H → μμμμ)) (%)
10
1
10^{-1}
50
100
150
200
250
300
350
400
450
500
$p_{T,min}^{H}$ [GeV]

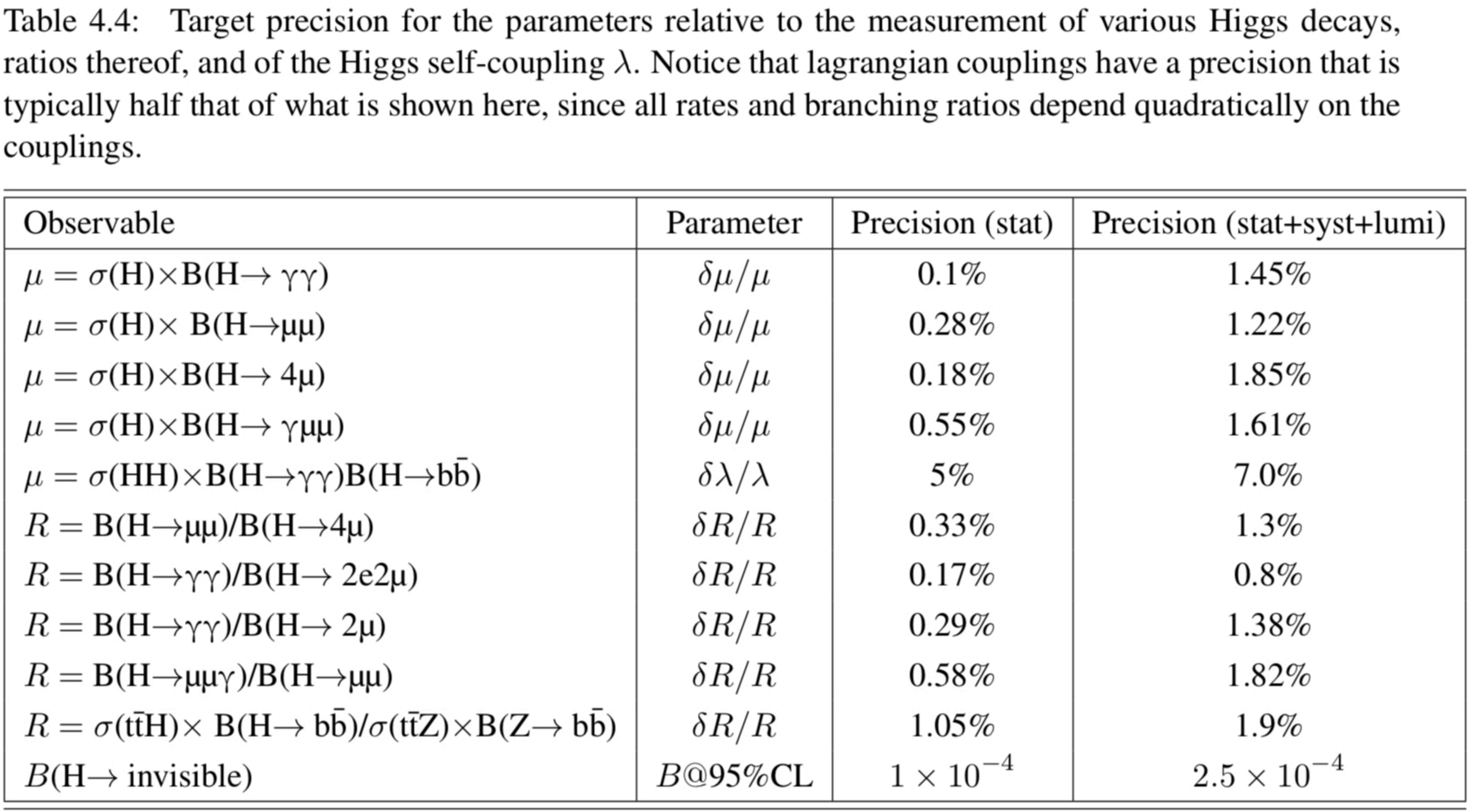


Table 4.4: Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)\mathrm{B}(\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mathrm{e}2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(\mathrm{t}\bar{\mathrm{t}}\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}})/\sigma(\mathrm{t}\bar{\mathrm{t}}\mathrm{Z})\times\mathrm{B}(\mathrm{Z}\to\mathrm{b}\bar{\mathrm{b}})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\to$ invisible$)$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Importance of standalone precise “ratios-of-BRs" measurements:

- independent of α_S, m_b, m_c, Γ_{inv} systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

BR(H→γγ)/BR(H→ZZ*)

loop-level tree-level

BR(H→μμ)/BR(H→ZZ*)

2nd gen’n Yukawa gauge coupling

BR(H→γγ)/BR(H→Zγ)

different EW charges in the loops of the two procs

BR(H→inv)/BR(H→γγ)

tree-level neutral loop-level charged

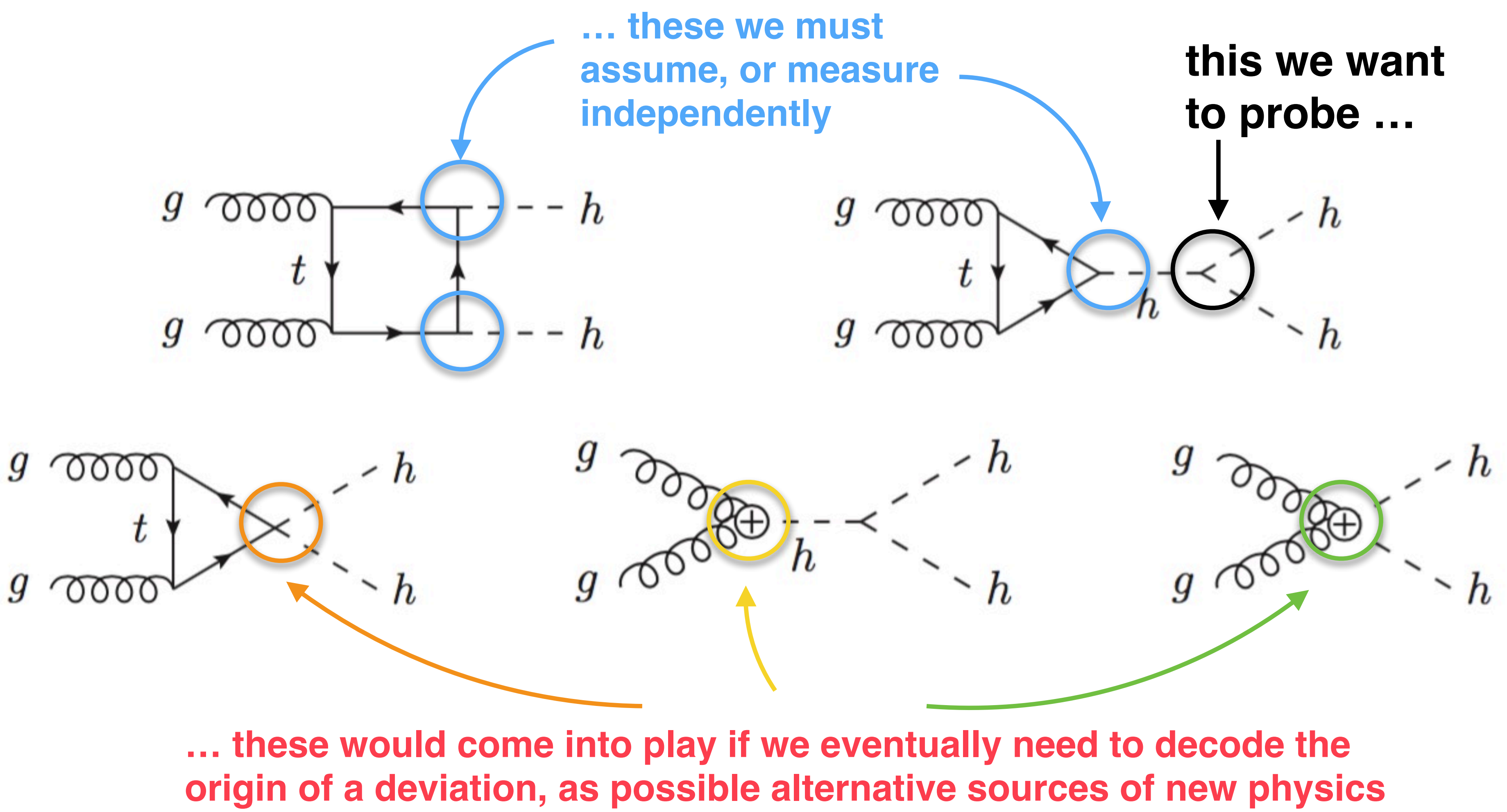
Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65** $^{(*)}$
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4** $^{(*)}$
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95** $^{(**)}$
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9** $^{(*)}$
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**6.5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4lept) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Extracting Higgs self-coupling from gg→HH at FCC-hh



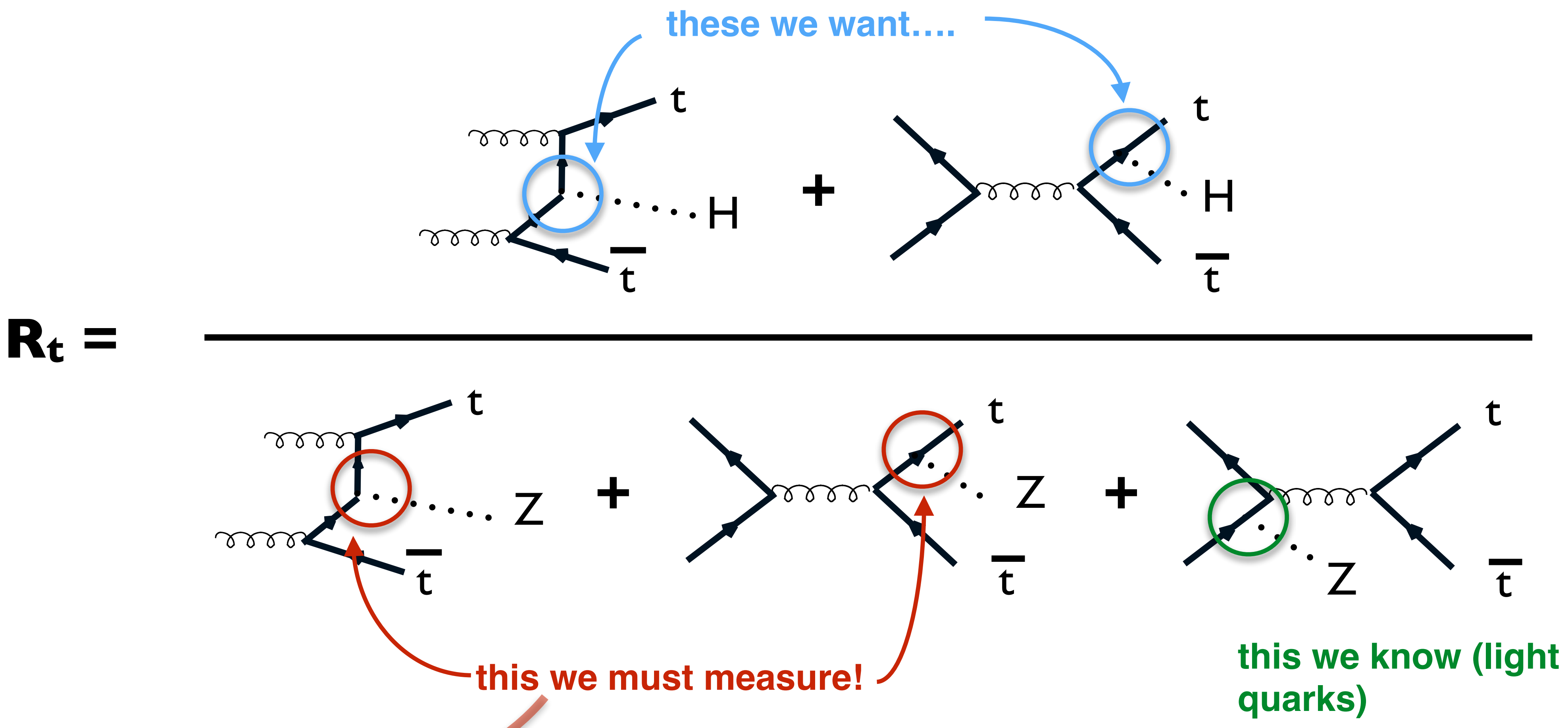
… these we must assume, or measure independently

this we want to probe …

… these would come into play if we eventually need to decode the origin of a deviation, as possible alternative sources of new physics

Direct measurement of ttH coupling: from $R_t = \sigma(ttH)/\sigma(ttZ)$

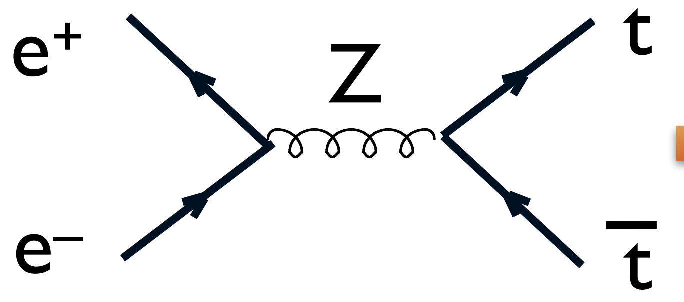
FCC-hh can measure R_t with $\Delta R_t/R_t \sim 2\%$

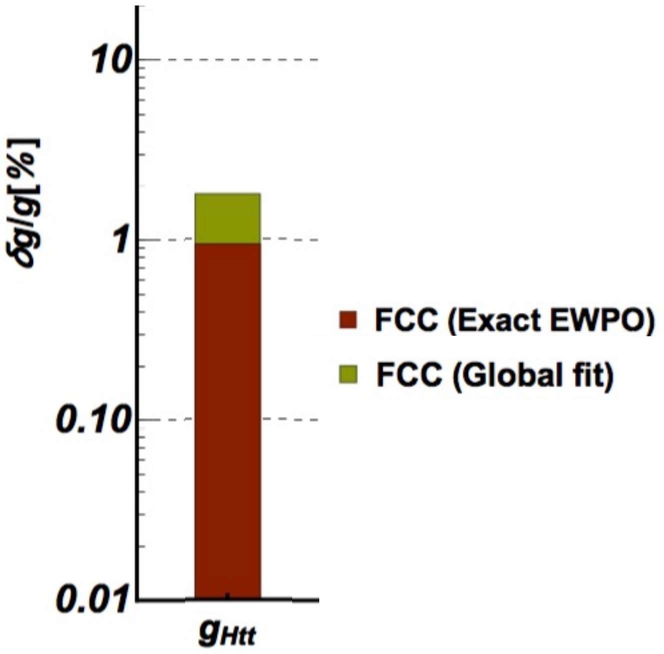


these we want….

this we must measure!

this we know (light quarks)





δλ/λ=5% from gg→HH assuming SM inputs

δλ/λ ~ 10% from global fit

Higgs self-coupling, gg→HH

From the detector performance studies:

Pheno-level studies:

	bbγγ	bbZZ[→4l]	bbWW[→2jlν]	4b+j	2b2τ+j
δκλ (%)	6.5	14	40	30	8

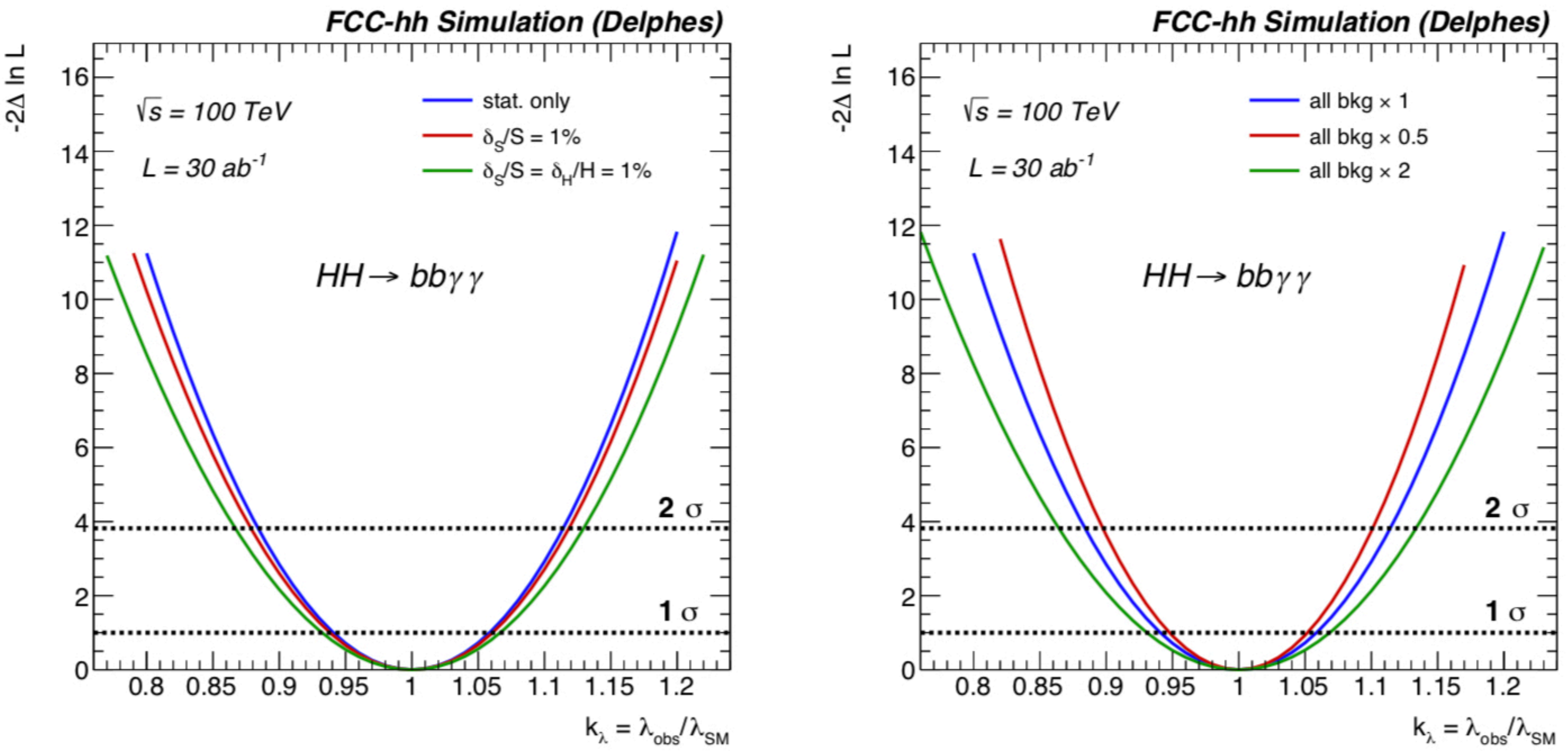
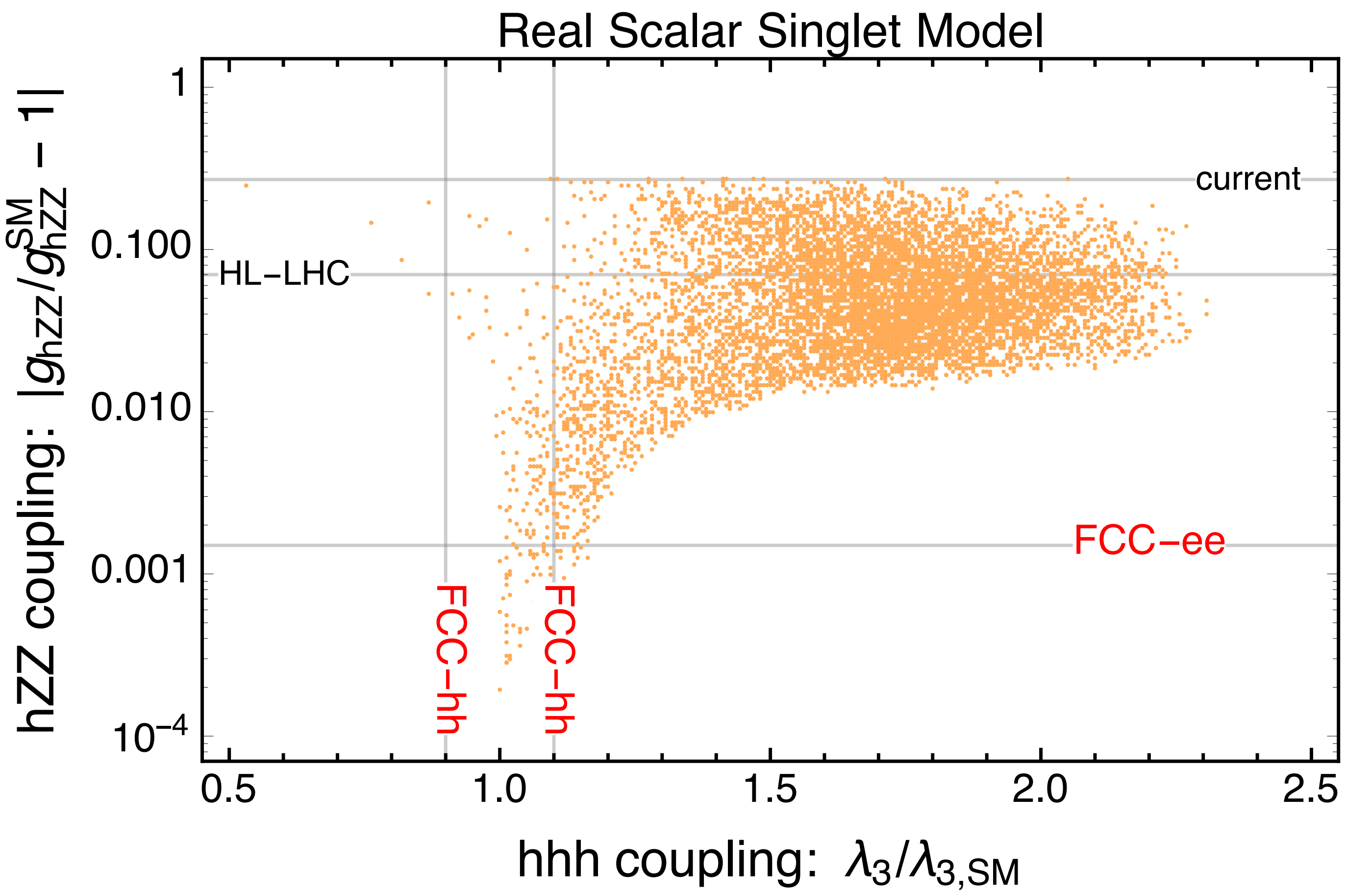


Figure 10.4: Expected precision on the Higgs self-coupling modifier κ_λ with no systematic uncertainties (only statistical), 1% signal uncertainty, 1% signal uncertainty together with 1% uncertainty on the Higgs backgrounds (left) and assuming respectively $\times 1$, $\times 2$, $\times 0.5$ background yields (right).)

Example of precision targets: constraints on models with 1st order phase transition

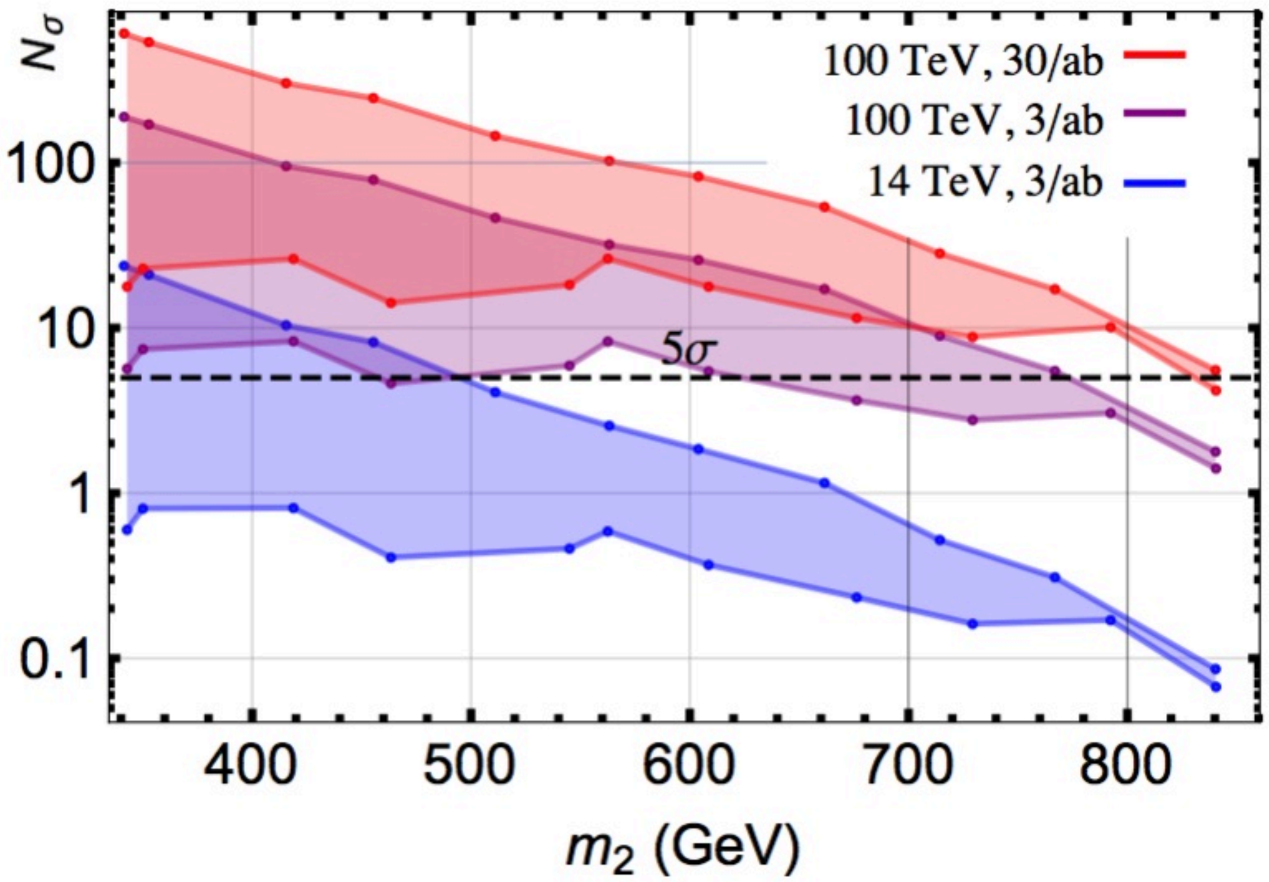
$$V(H,S) = -\mu^2\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right)S$$
$$+\frac{a_2}{2}\left(H^\dagger H\right)S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

Direct detection of extra Higgs states at FCC-hh



$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

$(h_2 \sim S, \quad h_1 \sim H)$

Precision vs sensitivity

- We often talk about "**precise**" Higgs measurements. What we actually aim at is "**sensitive**" tests of the Higgs properties, where *sensitive* refers to the ability to reveal BSM behaviours.
- ***Sensitivity*** may not require extreme precision
  - Going after "sensitivity", rather than *just* precision, opens itself new opportunities …

High-Q² observables : precision vs dynamic reach

$$L = L_{SM} + \frac{1}{\Lambda^2} \sum_k \mathcal{O}_k + \cdots$$

$$O = | \langle f|L|i\rangle |^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots\right]$$

For H decays, or inclusive production, $\mu \sim O(v, m_H)$

$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$$

⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

For H production off-shell or with large momentum transfer Q, $\mu \sim O(Q)$

$$\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$$

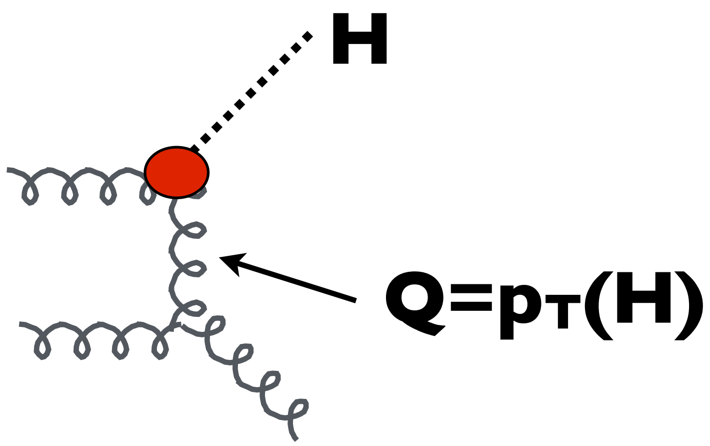
⇒ **kinematic reach** probes large Λ even if precision is “low”

e.g. δO=10% at Q=1.5 TeV ⇒ Λ~5 TeV

Complementarity between precise measurements at ee collider and large-Q studies at 100 TeV

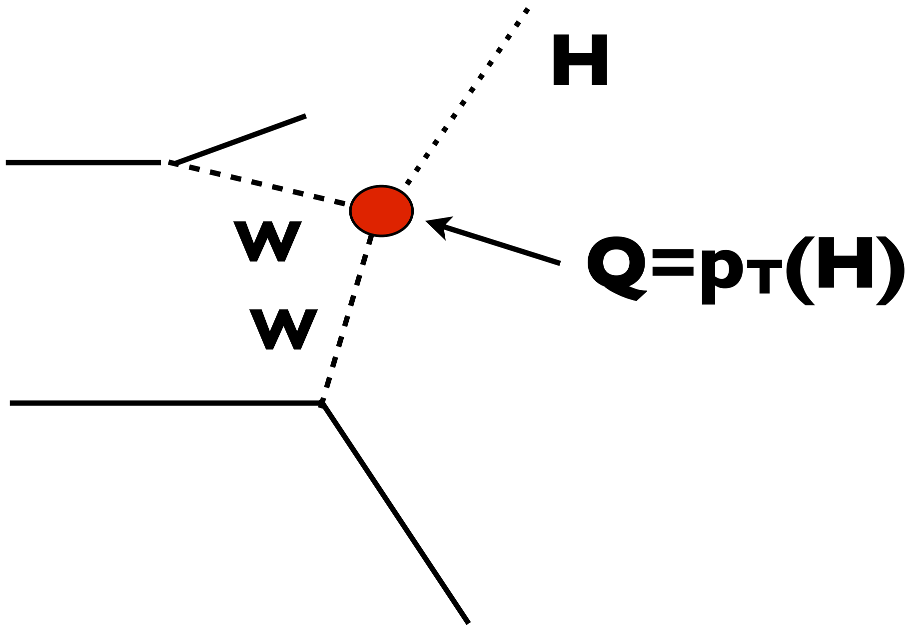
Examples

δBR(H→gg) ⟷

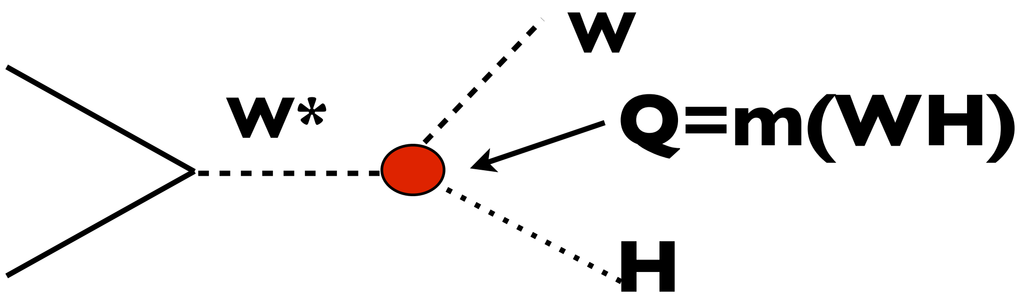


δBR(H→WW*) ⟷

(a)



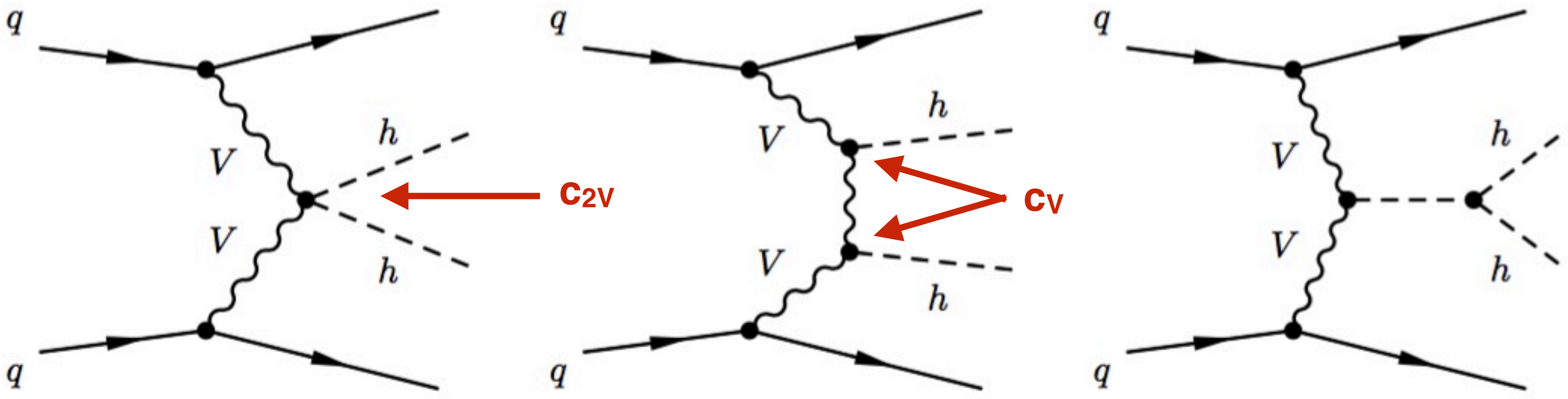
(b)



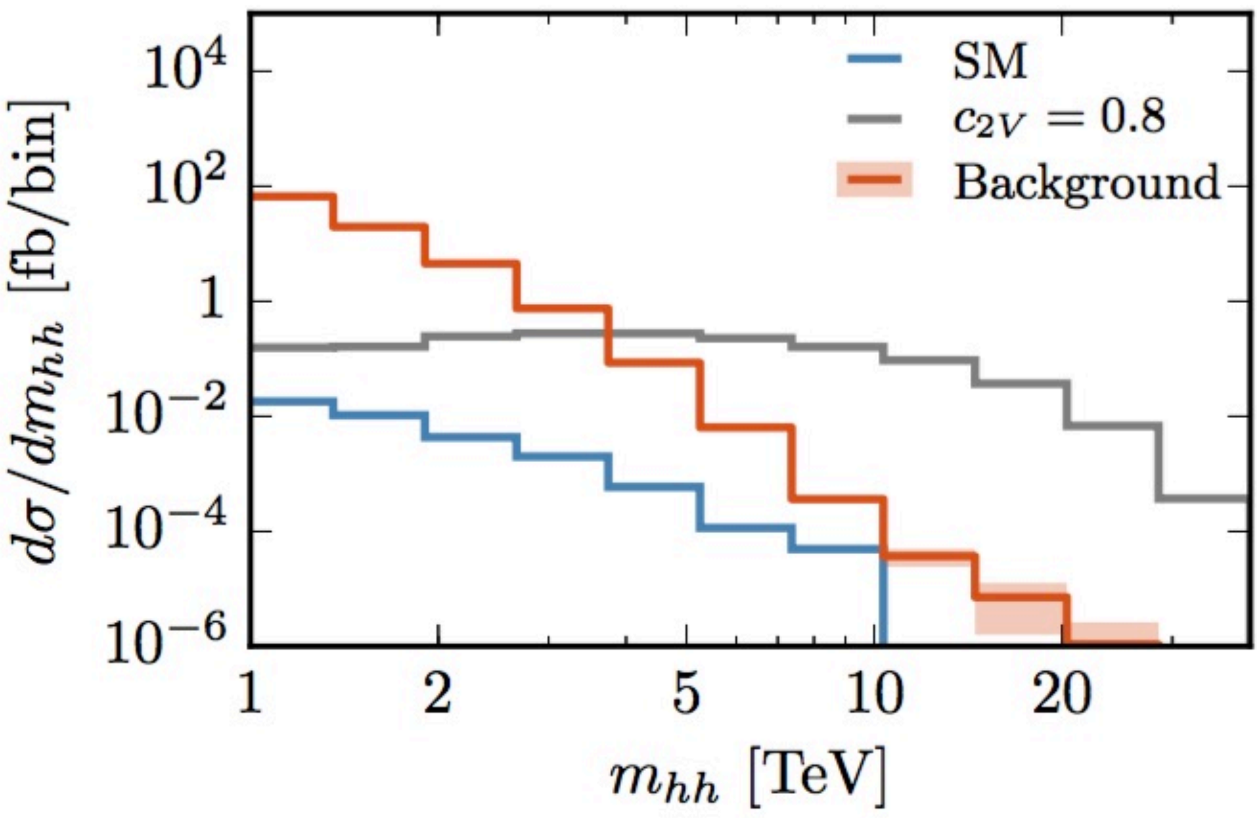
$$L_{D=6} = \frac{ig}{2}\frac{c_W}{\Lambda^2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu V^a_{\mu\nu}$$

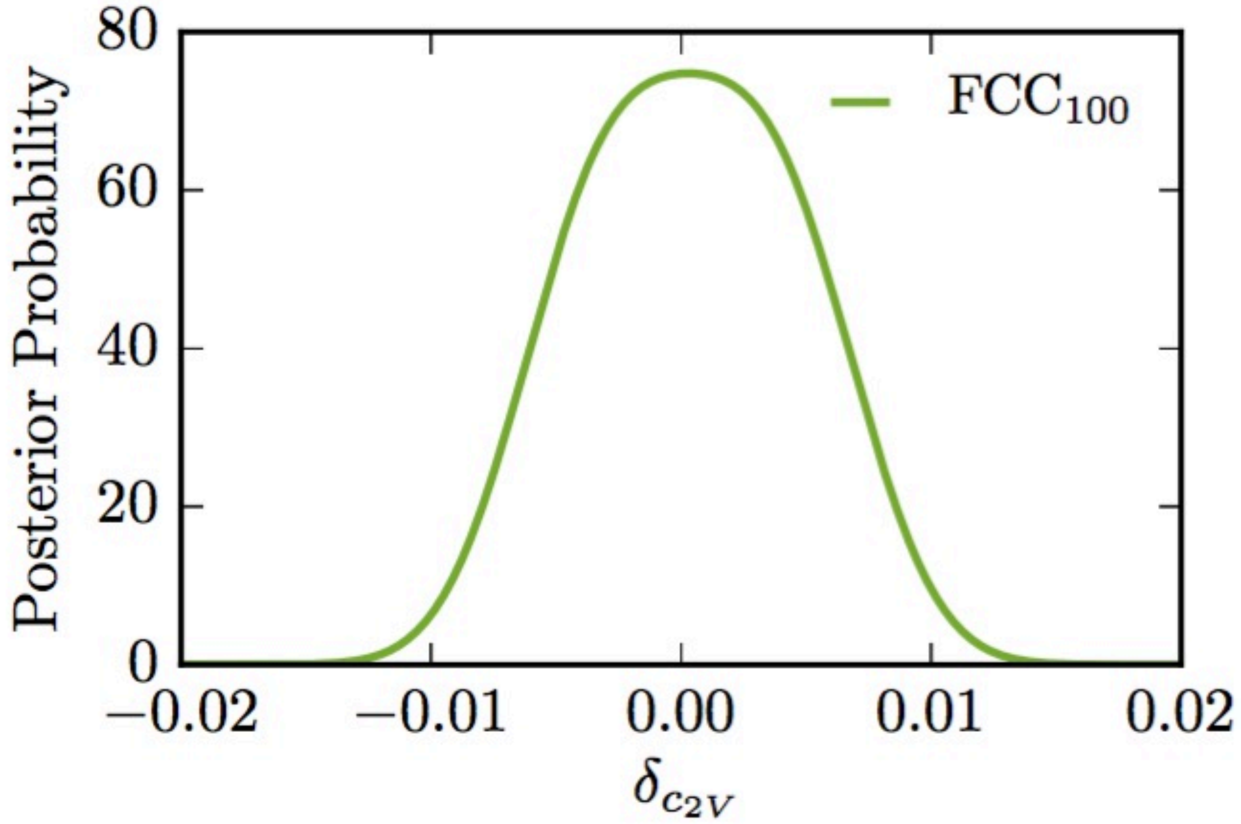
$$\Rightarrow \quad \frac{\sigma}{\sigma_{SM}} \sim \left(1 + c_W \frac{\hat{s}}{\Lambda^2}\right)^2$$

Example: high mass VV → HH

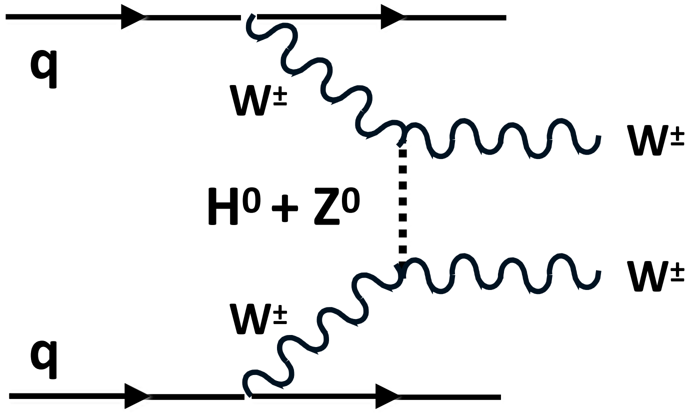


$A(\mathrm{V_L V_L} \to \mathrm{HH}) \sim \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$ · **where** $\begin{cases} c_V = g_{HVV}/g_{HVV}^{SM} \\ c_{2V} = g_{HHVV}/g_{HHVV}^{SM} \end{cases} \Rightarrow \left(c_{2V} - c_V^2\right)_{SM} = 0$

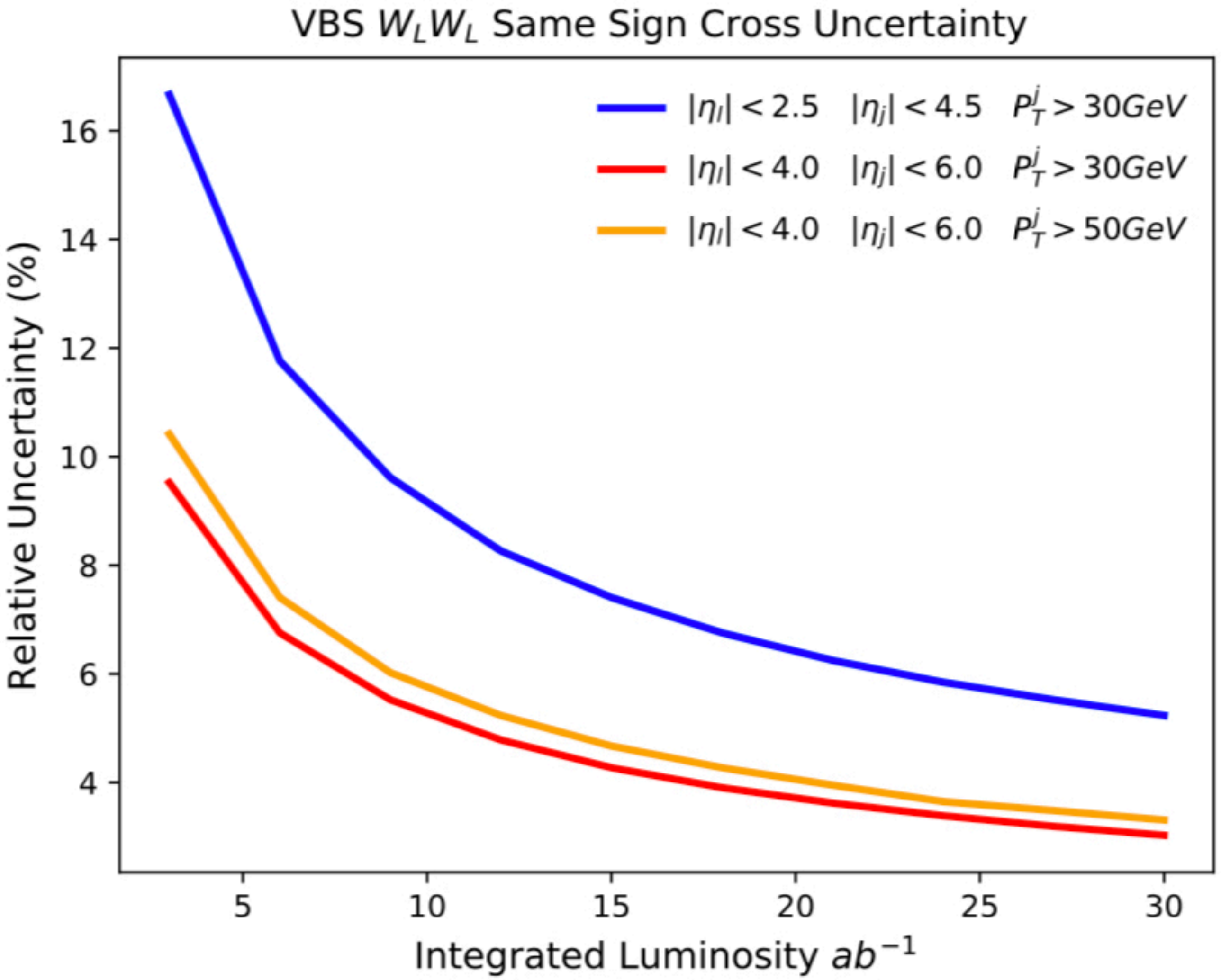




W_LW_L scattering



large m_{WW}



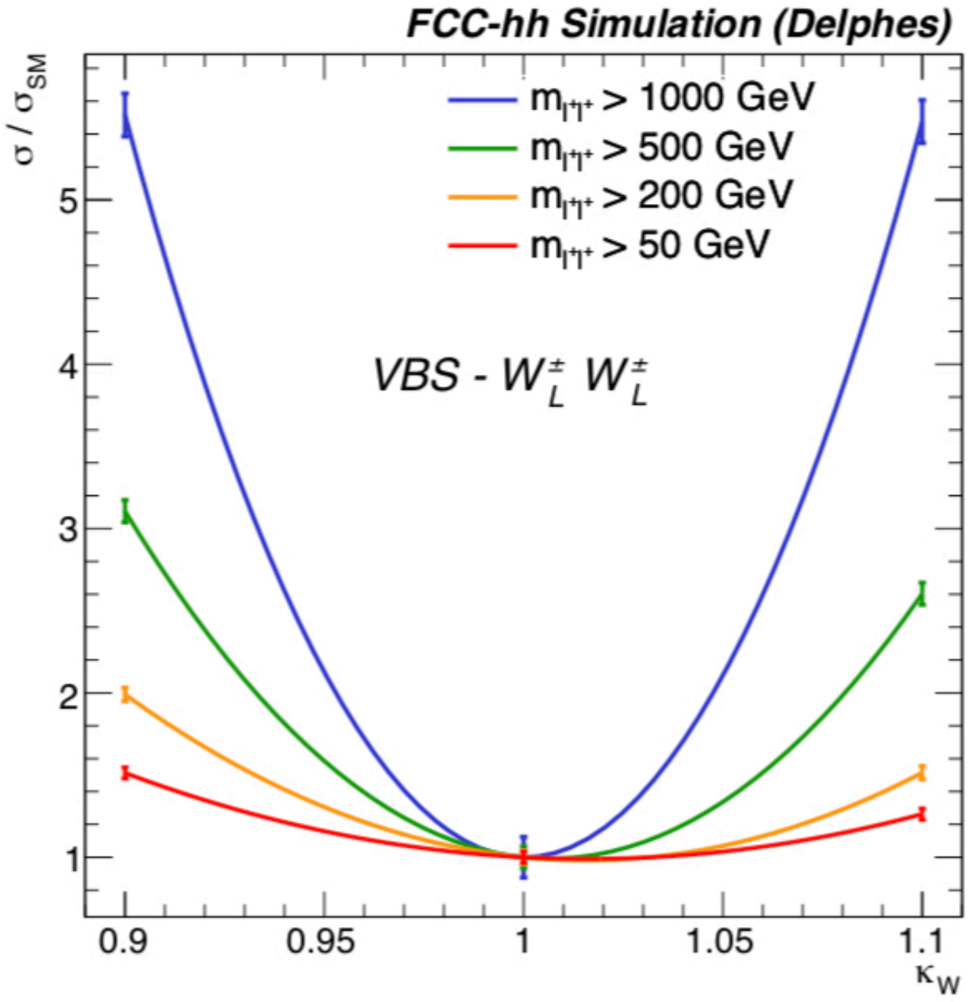


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \rightarrow HH$ process.

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

$$\kappa_W = \frac{g_{HWW}}{g^{SM}_{HWW}}$$

Example: high mass DY

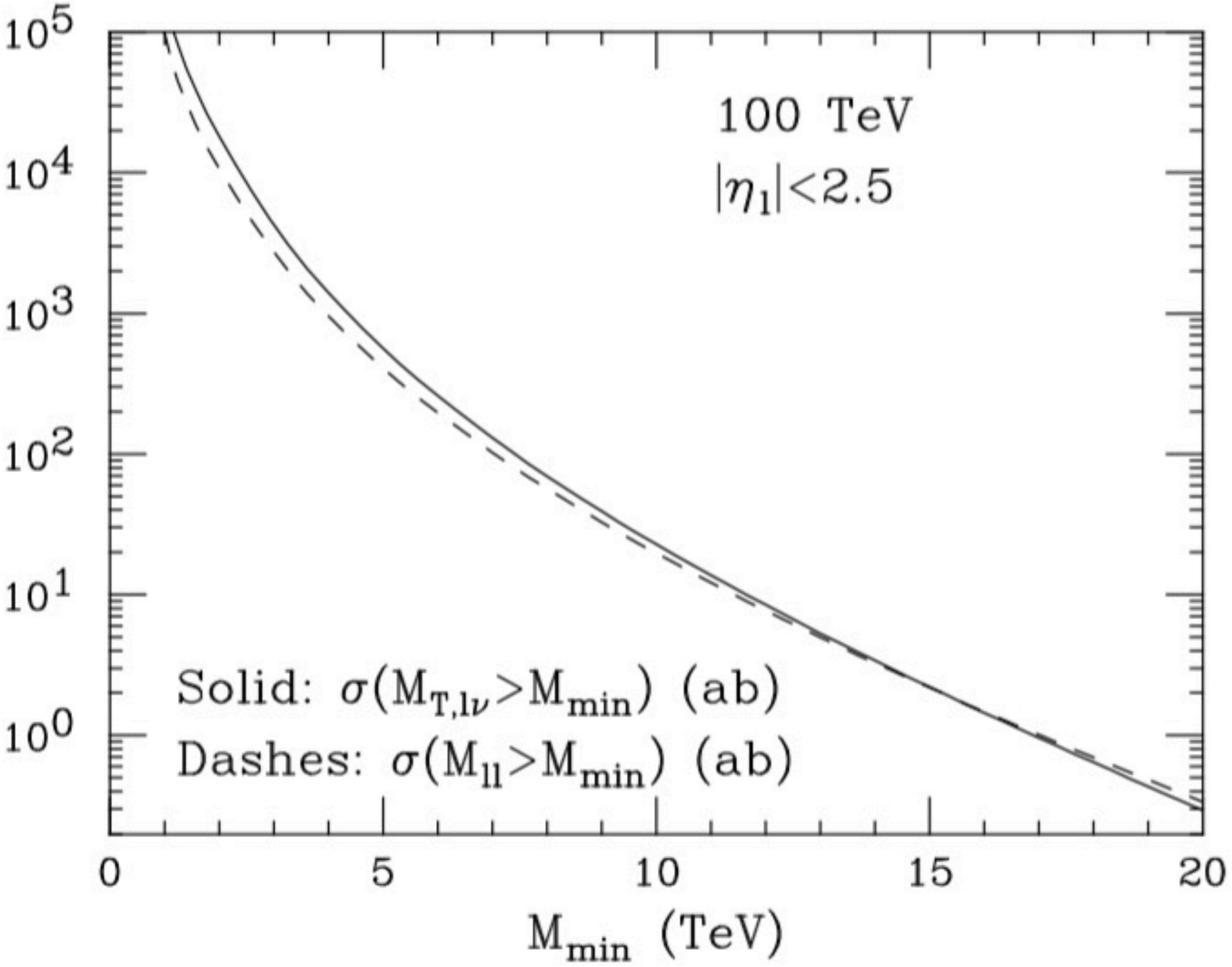
Farina et al,
arXiv:1609.08157

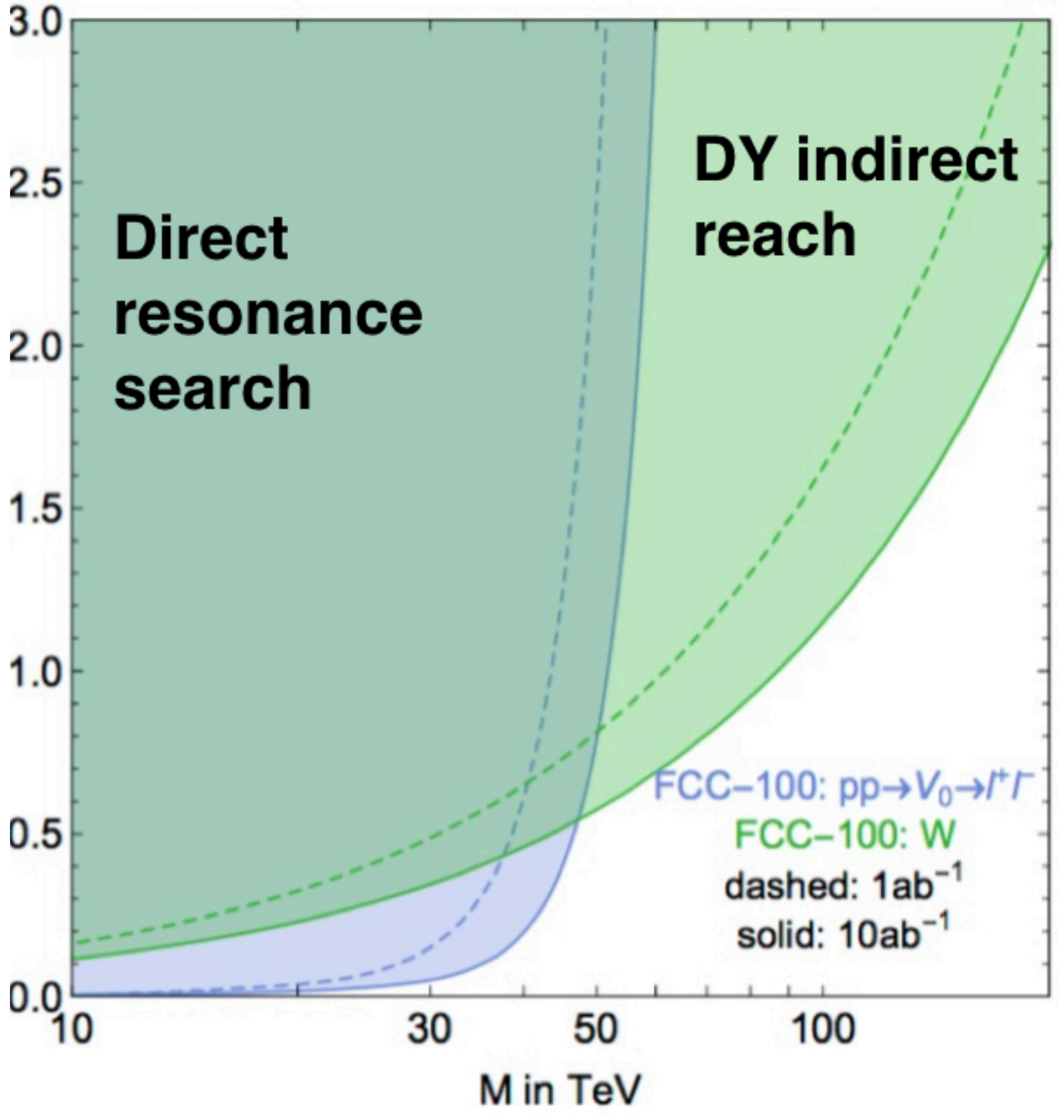
Constraints on Higher-dim op's

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

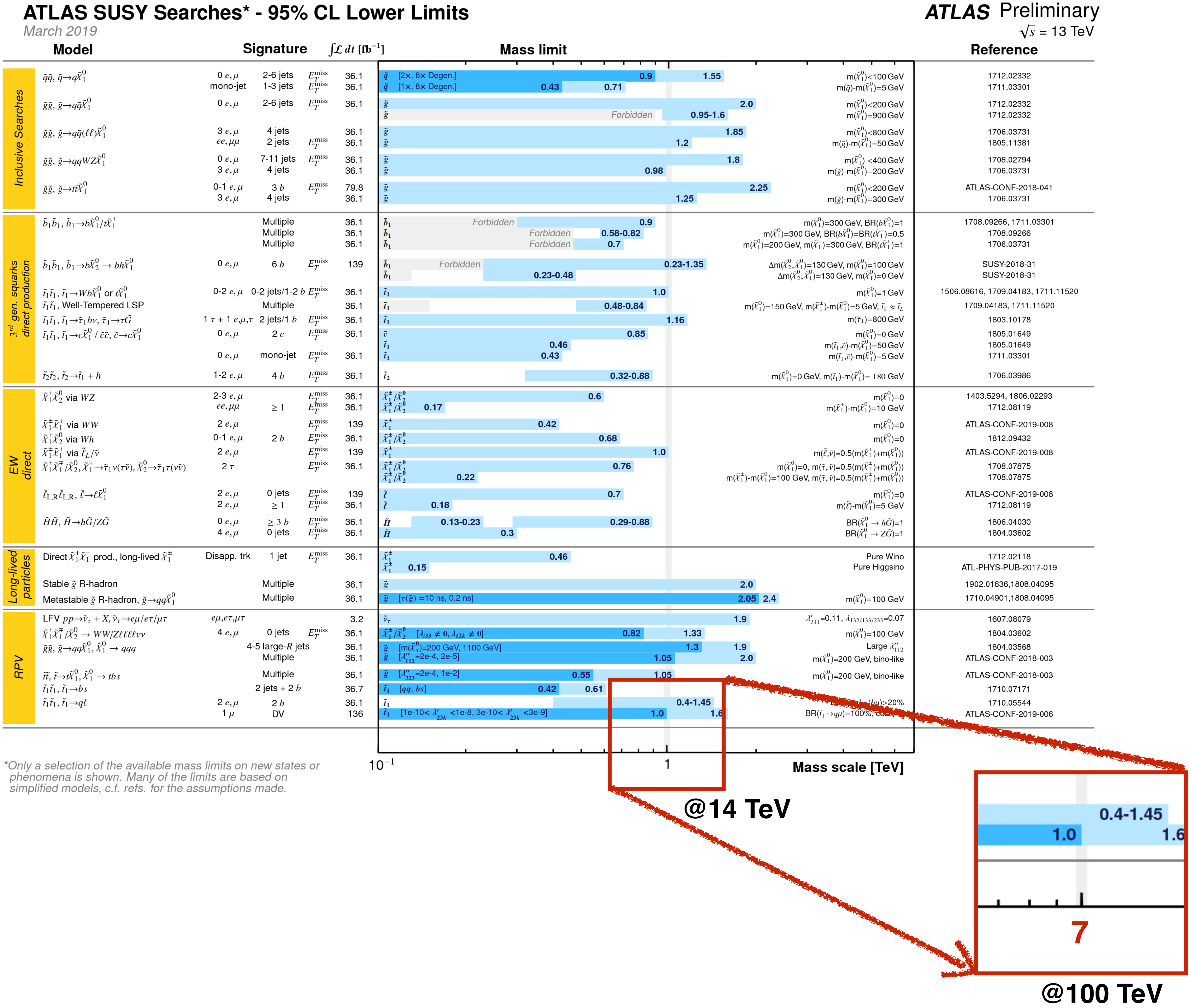
	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2\times 10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
W $\times 10^4$	$[-19, 3]$	±0.7	±0.45	±0.02	±4.2	±1.2	±3.6	±0.3	±0.5	±0.15
Y $\times 10^4$	$[-17, 4]$	±2.3	±1.2	±0.06	±1.8	±1.5	±3.1	±0.2	$\sim \pm 0.5$	$\sim \pm 0.15$

$W / 4m_W^2 \ < \ 1 / (100\ \text{TeV})^2$





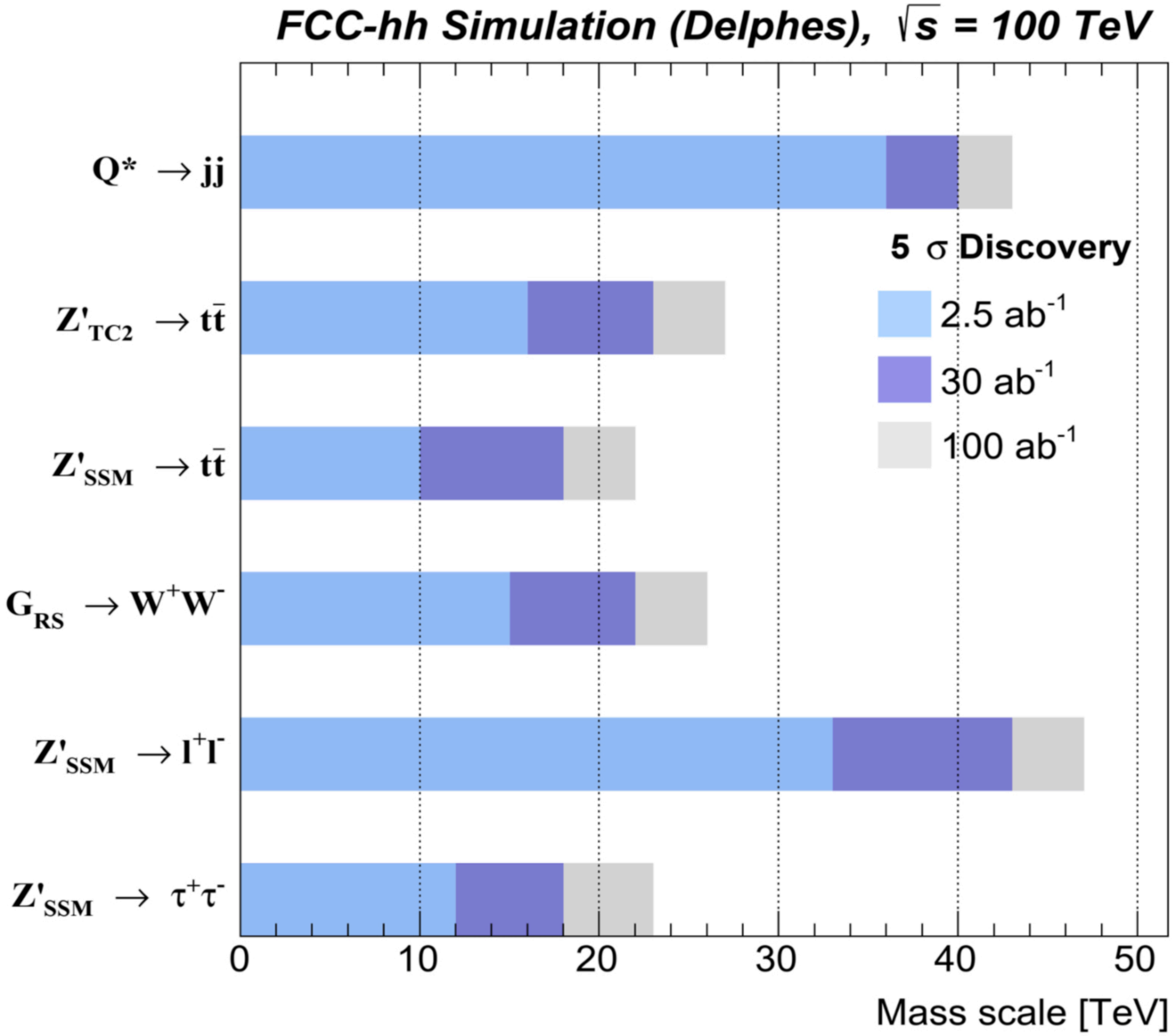
Direct discovery reach: the power of 100 TeV



@14 TeV

@100 TeV

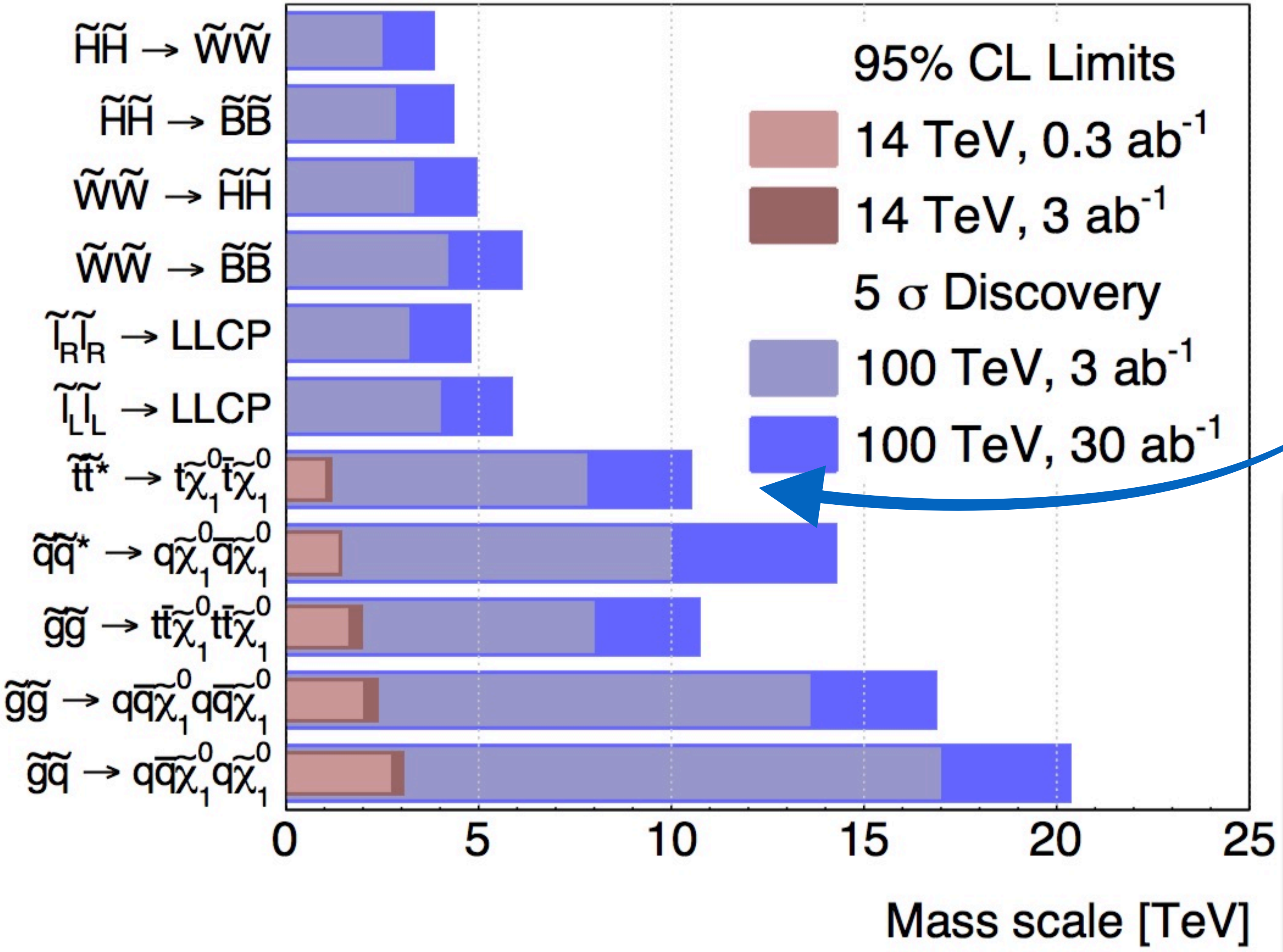
s-channel resonances



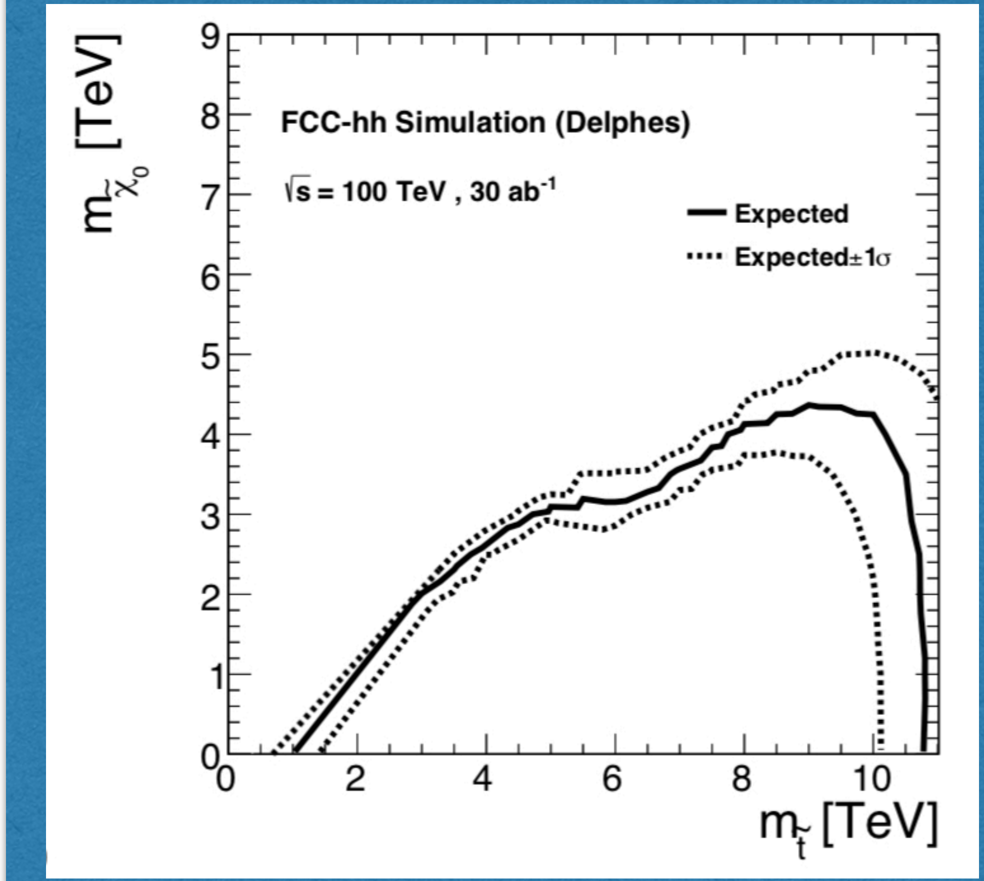
FCC-hh reach ~ 6 x HL-LHC reach

SUSY reach at 100 TeV

Early phenomenology studies



New detector performance studies



WIMP DM theoretical constraints

For particles held in equilibrium by pair creation and annihilation processes, (χ χ ↔ SM)

$$\Omega_{\rm DM} h^2 \sim \frac{10^9 {\rm GeV}^{-1}}{M_{\rm pl}} \frac{1}{\langle \sigma v \rangle}$$

For a particle annihilating through processes which do not involve any larger mass scales:

$$\langle \sigma v \rangle \sim g_{\rm eff}^4 / M_{\rm DM}^2$$

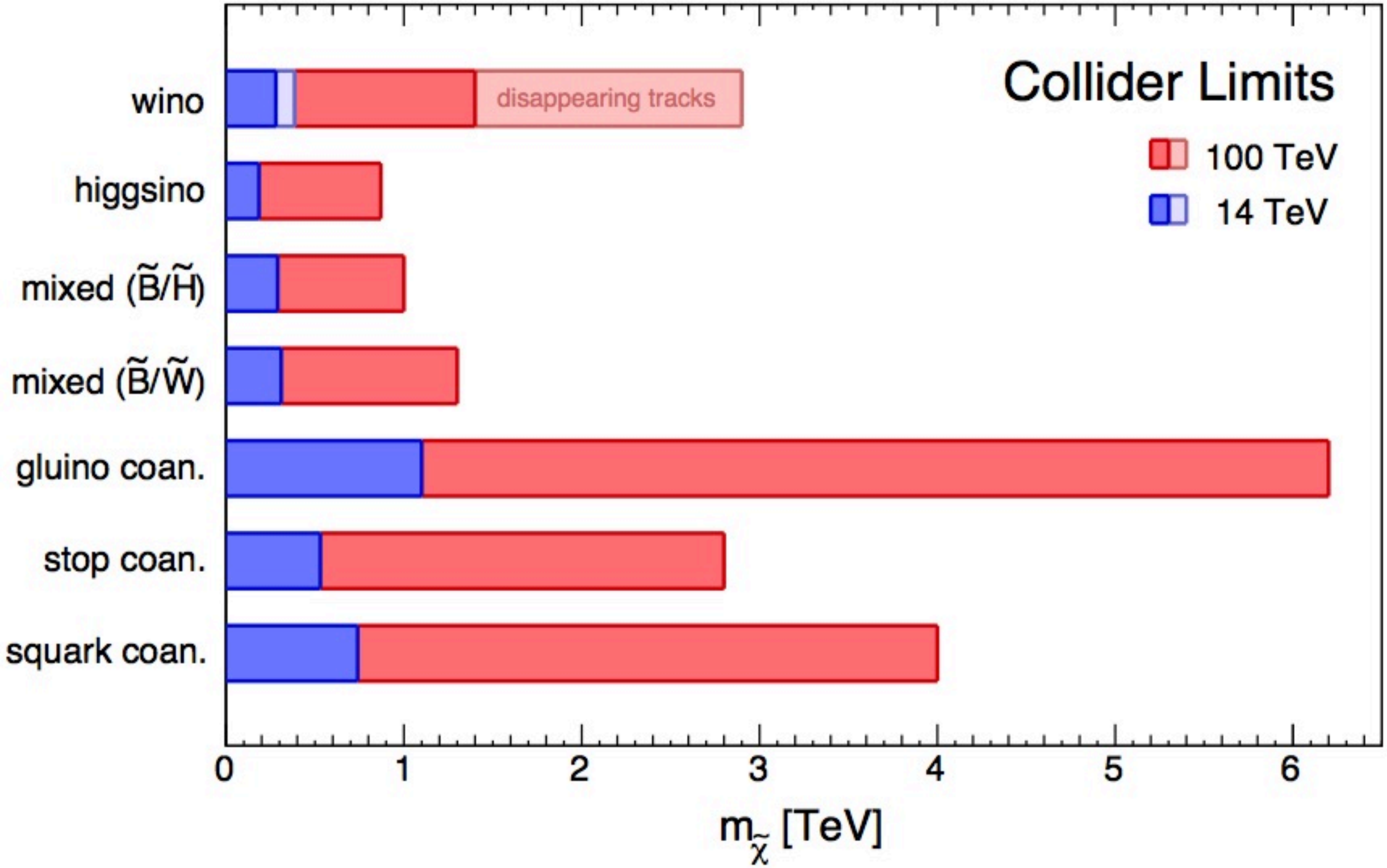
$$\Omega_{\rm DM} h^2 \sim 0.12 \times \left(\frac{M_{\rm DM}}{2\ {\rm TeV}} \right)^2 \left(\frac{0.3}{g_{\rm eff}} \right)^4$$

$$\Omega_{wimp}\, h^2 \lesssim 0.12$$

$$M_{wimp} \lesssim 2\ {\rm TeV} \left(\frac{g}{0.3} \right)^2$$

DM reach at 100 TeV

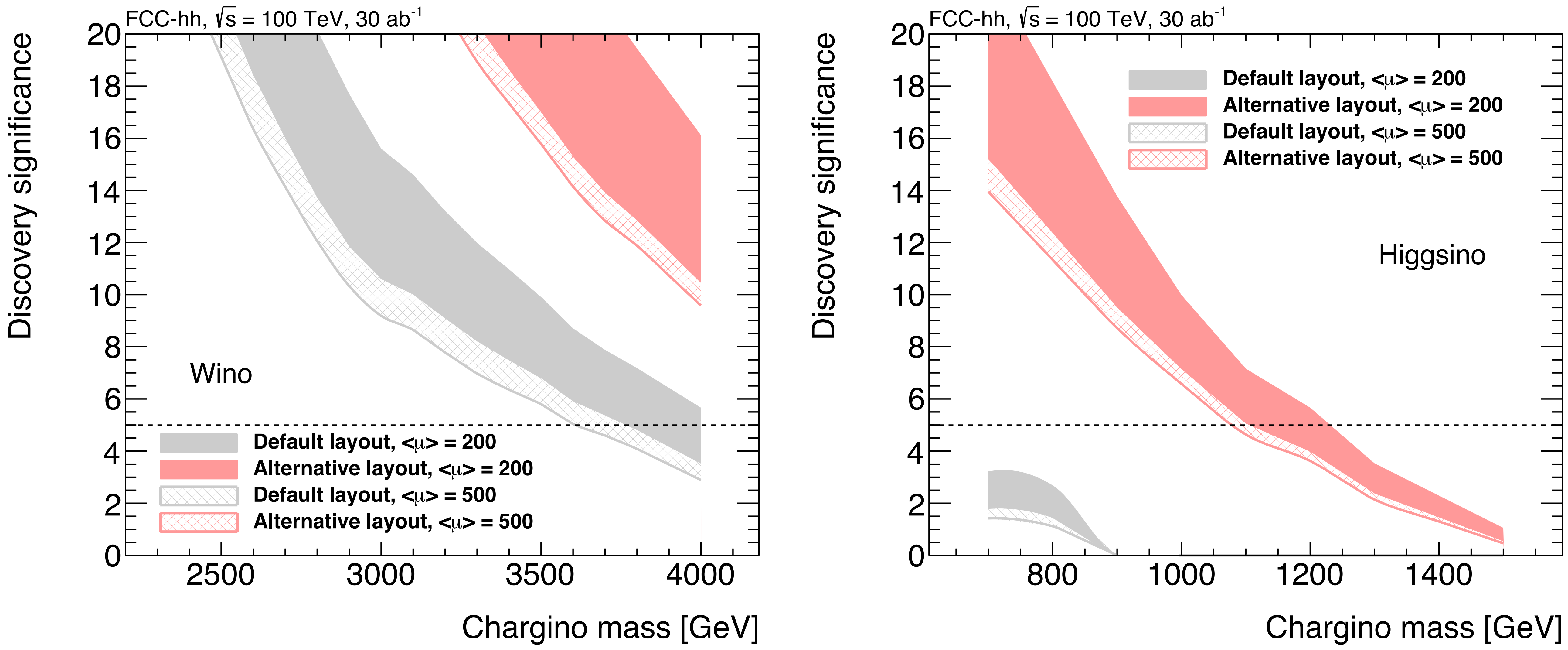
Early phenomenology studies



K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.

Disappearing charged track analyses

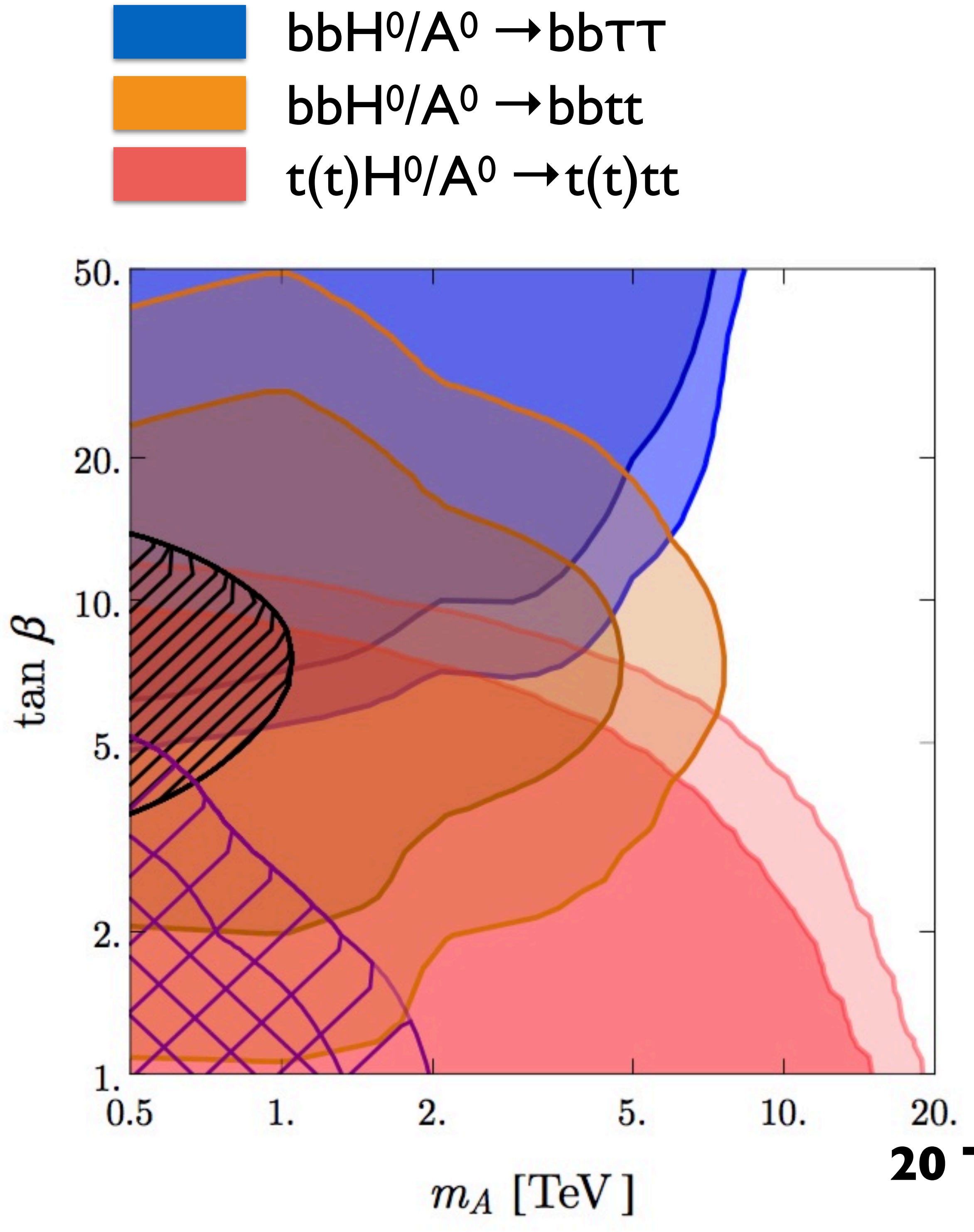
(at ~full pileup)



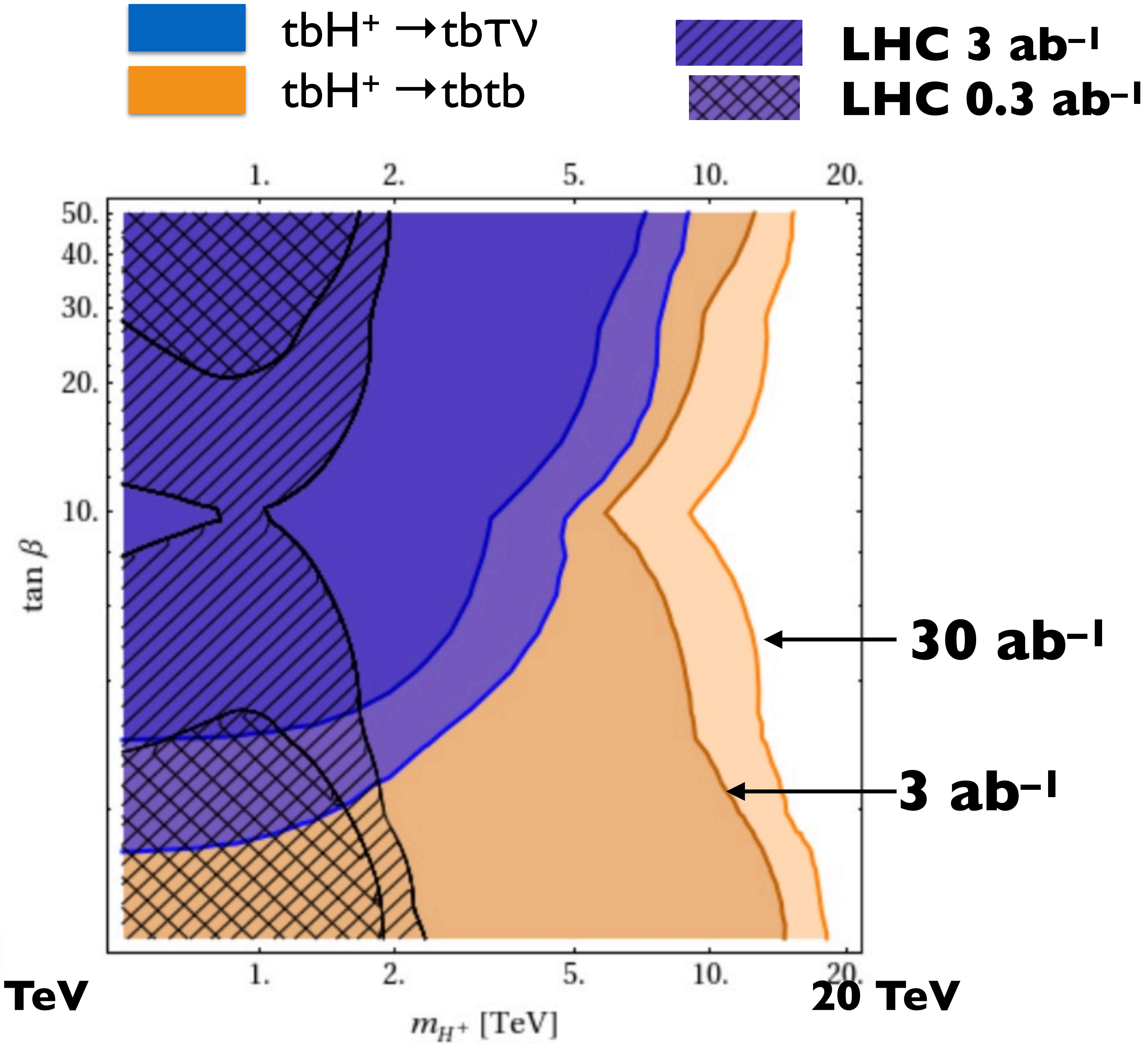
=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{wimp} \lesssim 2\ \mathrm{TeV} \left(\frac{g}{0.3}\right)^2$$

MSSM Higgs @ 100 TeV



20 TeV



N. Craig, J. Hajer, Y.-Y. Li, T. Liu, H. Zhang, arXiv:1605.08744

J. Hajer, Y.-Y. Li, T. Liu, and J. F. H. Shiu, arXiv:1504.07617

Final remarks

- The study of the SM will not be complete until we clarify the nature of the Higgs mechanism and exhaust the exploration of phenomena at the TeV scale: many aspects are still obscure, many questions are still open.

- The combination of a versatile high-luminosity e^+e^- circular collider, with a follow-up pp collider in the 100 TeV range, appears like the ideal facility for the post-LHC era
  - *complementary and synergetic precision studies of EW, Higgs and top properties*
  - *energy reach to allow direct discoveries at the mass scales possibly revealed by the precision measurements*
  - *flavor factory at the Z pole, heavy ions and ep collisions: extremely diversified program => broad community engagement*